High-energy hadron physics including possible spin projects at J-PARC

Shunzo Kumano

High Energy Accelerator Research Organization (KEK)

Graduate University for Advanced Studies (GUAS)

shunzo.kumano@kek.jp

http://research.kek.jp/people/kumanos/

Berkeley Summer Program on Nucleon Spin Physics

LBL, Berkeley, USA

http://www-nsdth.lbl.gov/~fyuan/spin09/

Note: The latter half is based on my personal studies rather than an overview of the J-PARC project.

June 1 – 12, 2009
(Talk on June 12)

Contents

1. **J-PARC facility**
2. **Low-energy hadron physics** (→ short comments by skipping most slides)

   Strangeness nuclear physics, Exotic hadrons,
   Hadrons in nuclear medium, Neutrino-hadron interactions

3. **High-energy hadron physics**
   - **Hard interactions**

     Elastic scattering, Color transparency, Short-range NN interactions,
     Generalized Parton Distributions (GPDs)

   - **Structure functions, Fragmentation functions**

     $\bar{u}$ / $\bar{d}$ asymmetry, Nuclear PDFs, Polarized PDFs,
     Spin-1 structure, Fragmentation functions

   - **After major upgrades (polarization, heavy-ion ?)**

     Details of hadron spin, quark-hadron matters …

3. **Summary**

J-PARC Facility

J-PARC Location

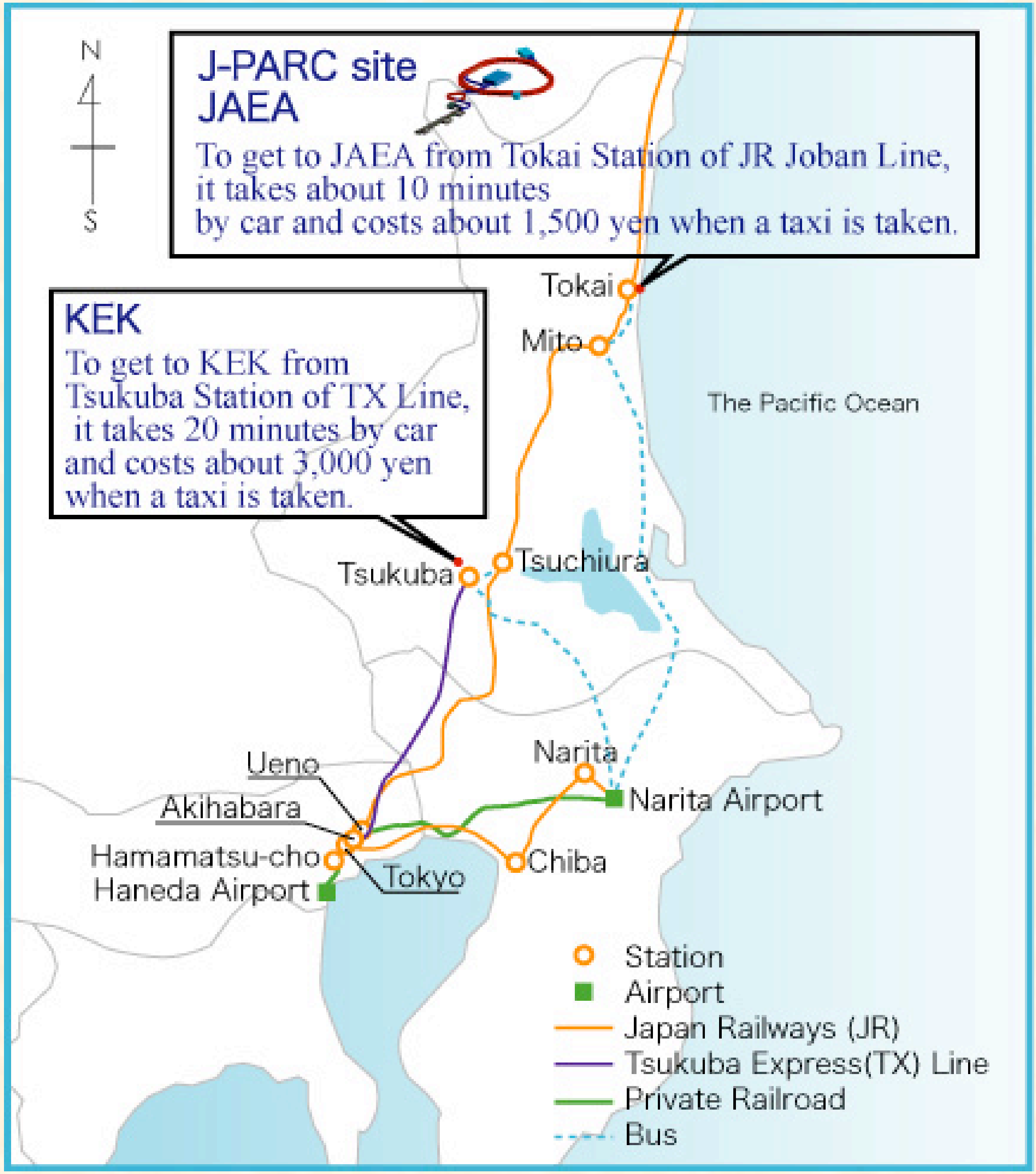
J-PARC
(Japan Proton Accelerator Research Complex)

http://j-parc.jp/index-e.html

Joint facility of JAEA and KEK

JAEA (Japan Atomic Energy Agency)

KEK (High Energy Accelerator Research Organization)

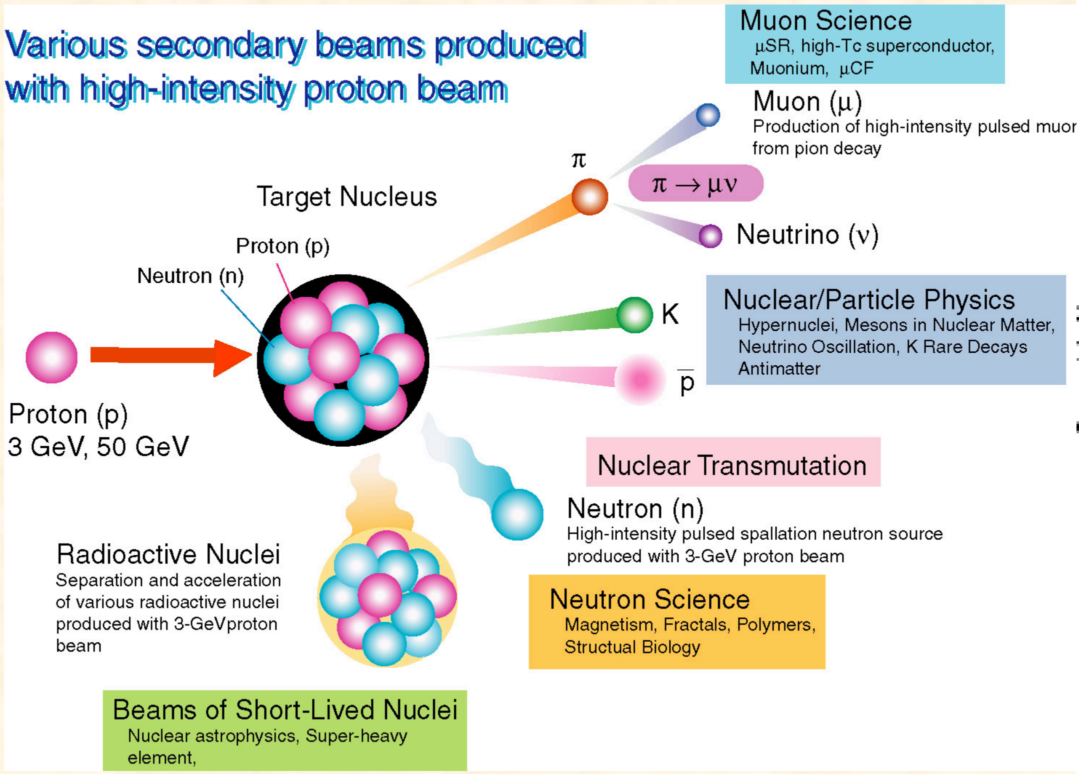


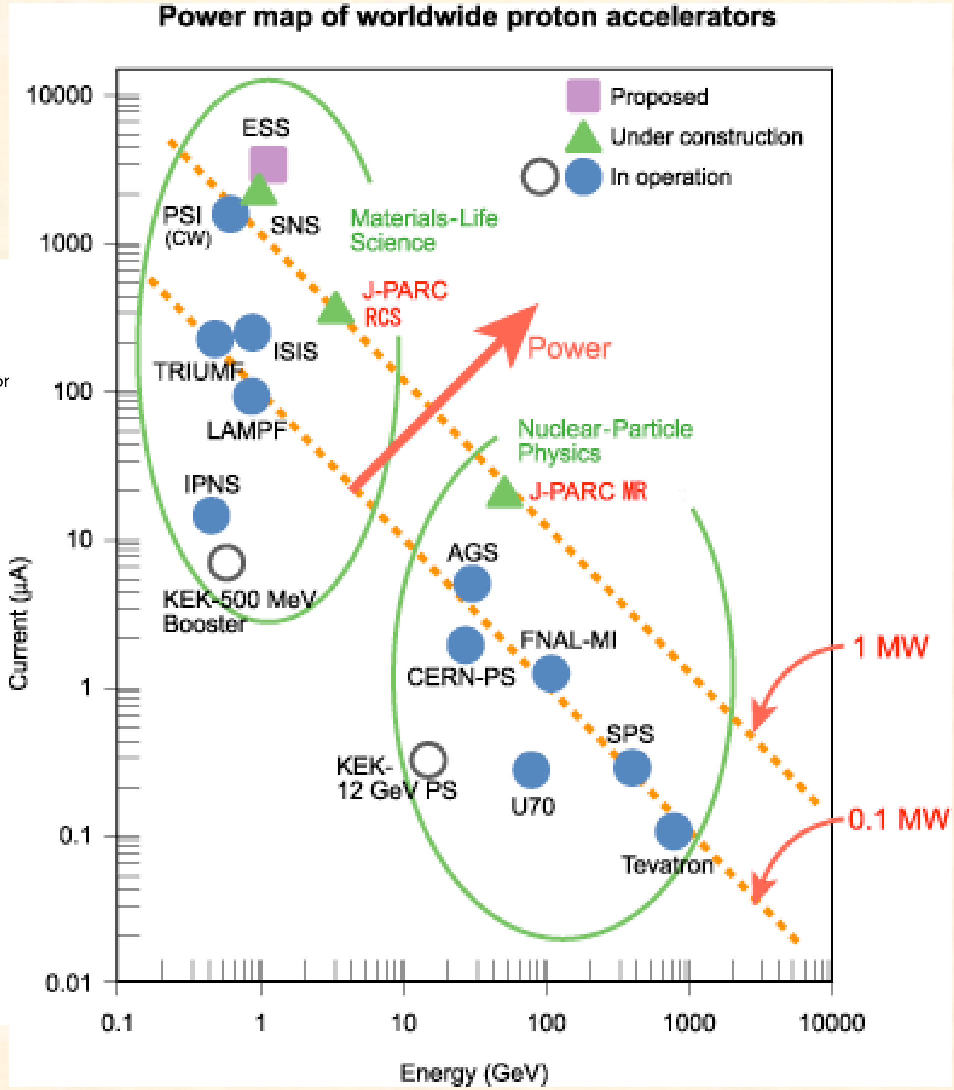
Bird's-eye view

Particle and Nuclear Physics

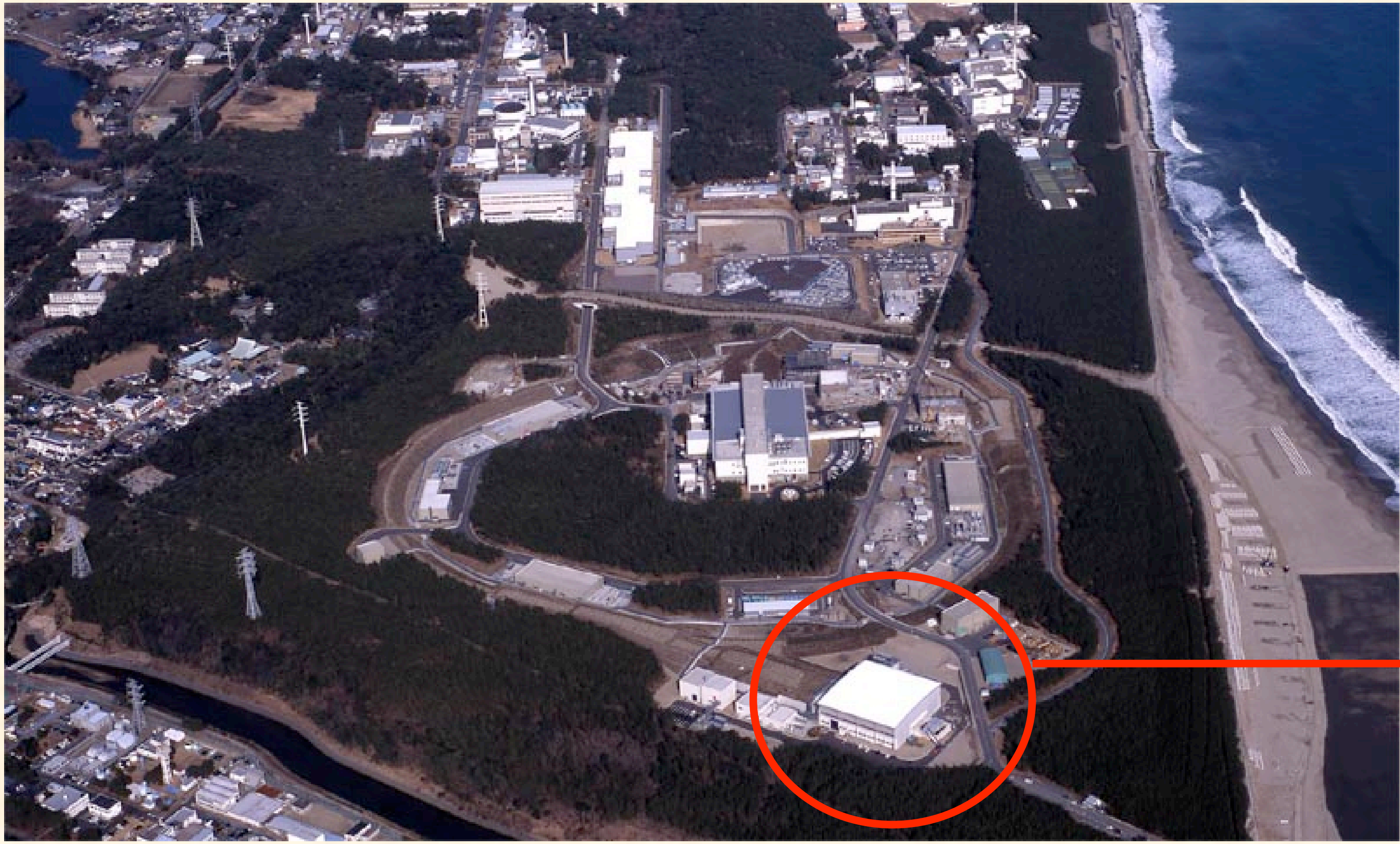
High-Intensity Frontier of Proton Accelerator

High-intensity proton beam
→ High-intensity secondary beams
(Neutrino, Kaon, Pion, Neutron …)





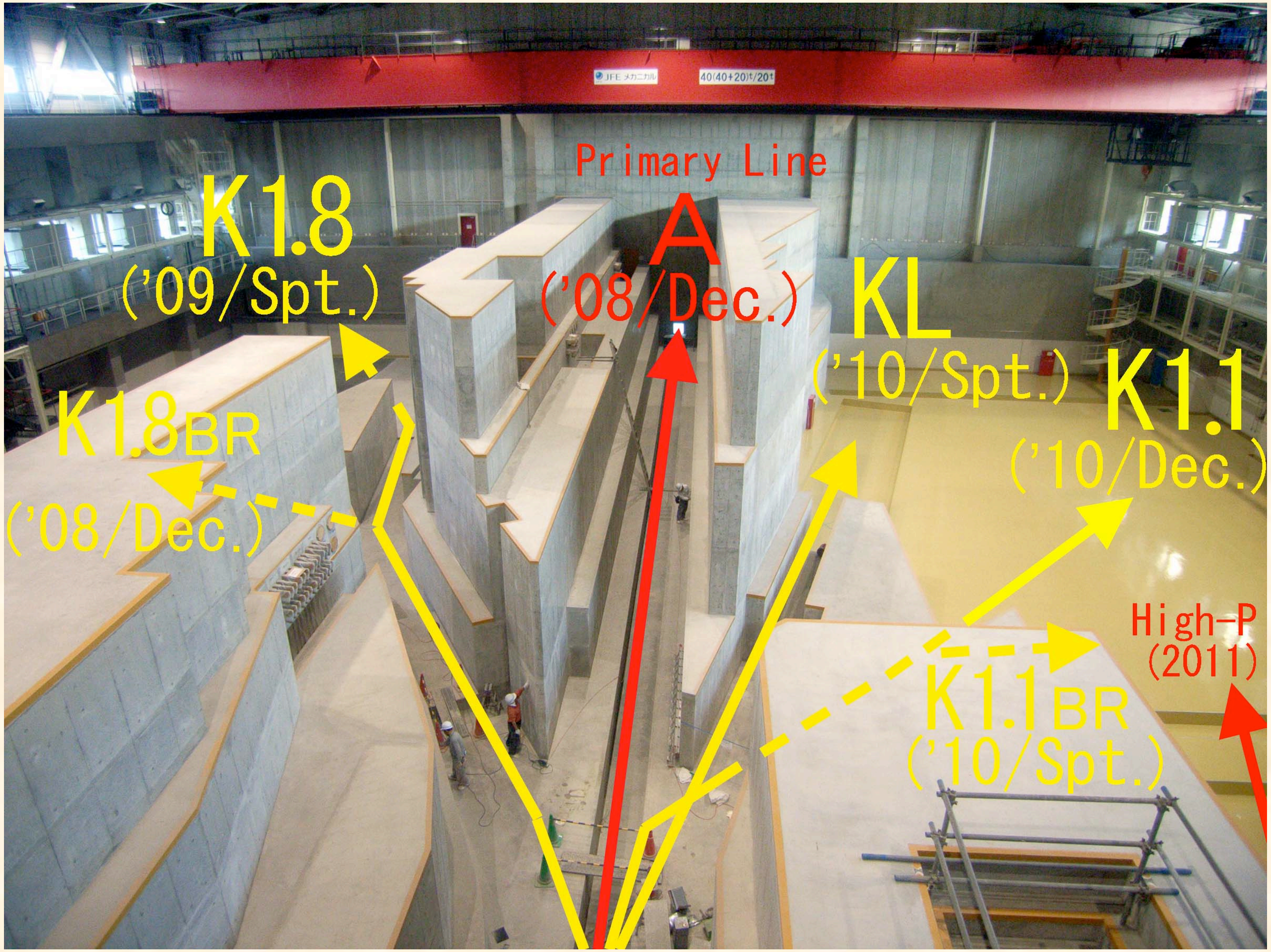
Aerial photograph on January 28, 2008



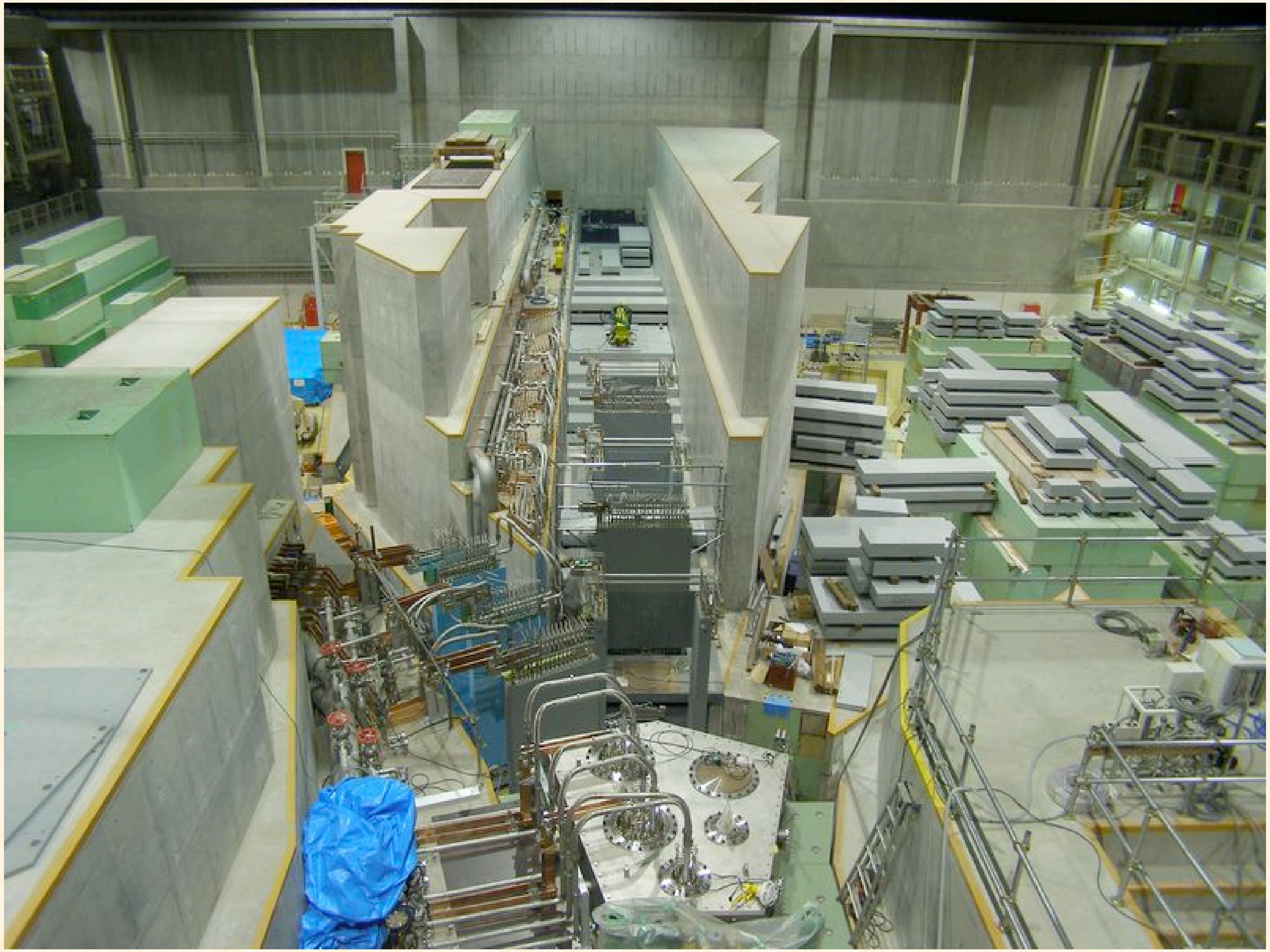
Hadron facility

May 23, 2008: Injection to Main Ring
Jan. 28, 2009 : Acceleration to 30 GeV
Apr. 13, 2009 : Kaon beam
Apr. 23, 2009 : Neutrino beam

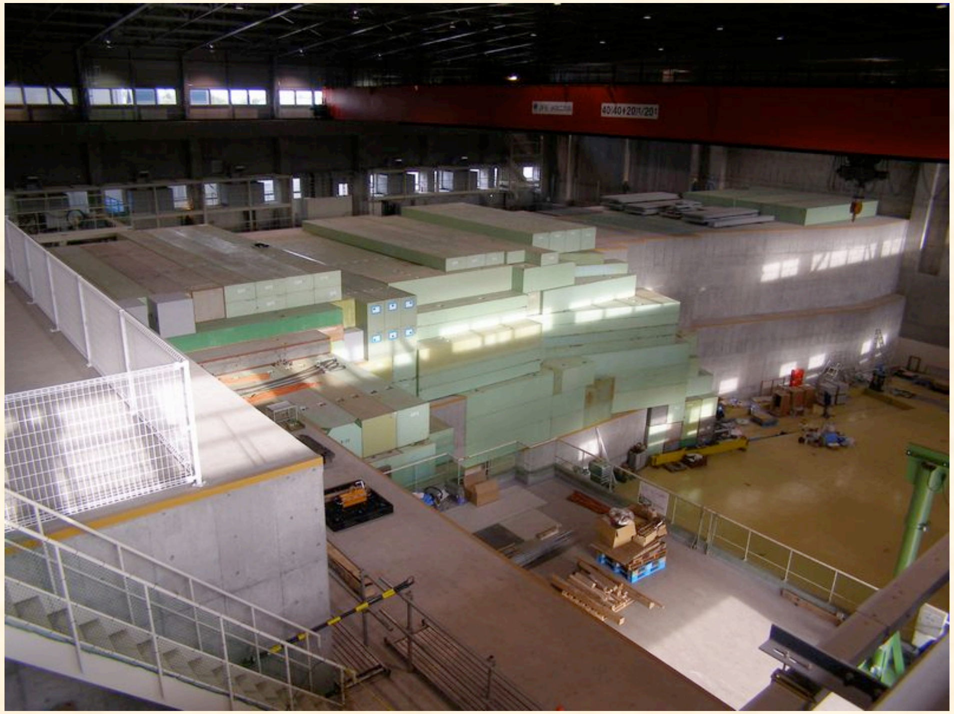
Hadron facility in May 2007 and a possible schedule for beam lines



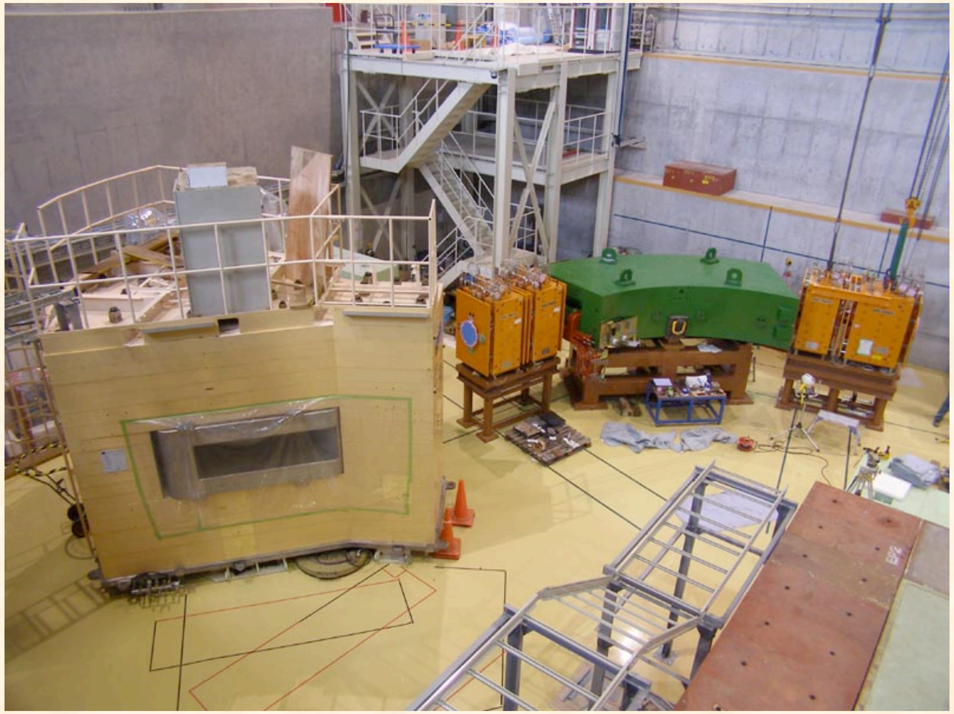
Hadron Facility on November 14, 2008



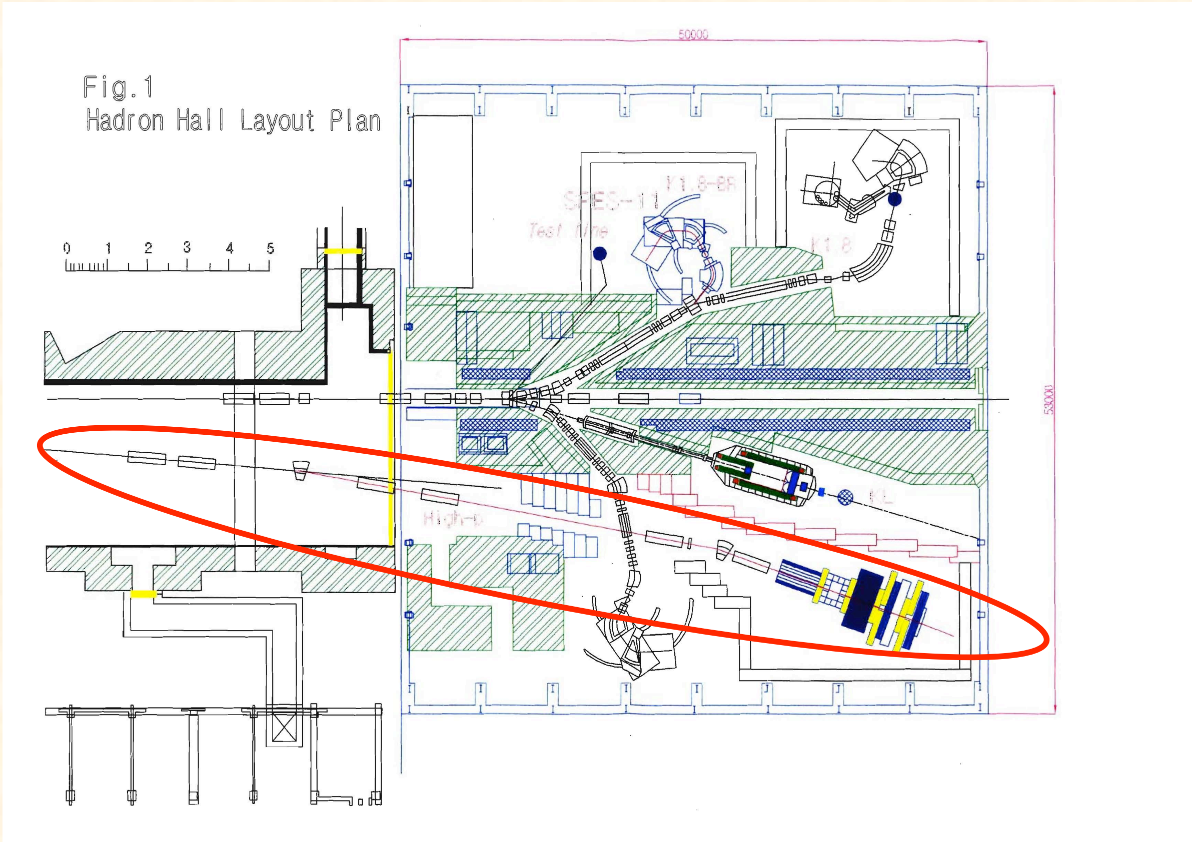
Hadron Hall
on Jan. 13, 2009



K1.8 beamline
on May 12, 2009



High-Momentum Beam Line (30, 50 GeV Proton)



This beam line should be interesting for the audience of this workshop.

Hadron Physics at J-PARC

by adding comments from my own works

References

My talks on “Possible Hadron Physics at J-PARC”

Trieste (2006) http://www.pg.infn.it/hadronic06/
Ghent (2007) http://inwpent5.ugent.be/workshop07/
Mito (2008) http://j-parc.jp/NP08/
Trieste (2008) http://www.pg.infn.it/hadronic08/

J-PARC workshops on hadron physics

- J-PARC-HS05
  http://www-conf.kek.jp/J-PARC-HS05/program.html
- J-PARC-NP07
  http://www-conf.kek.jp/NP_JPARC/program.html
- J-PARC-NP08 http://j-parc.jp/NP08/
- Riken spin workshop for J-PARC
  http://rarfaxp.riken.jp/~ygoto/jparc-riken0804/
- Meeting on high-energy hadron physics at J-PARC
  http://www-conf.kek.jp/hadron08/hehp-jparc/

J-PARC spin projects are discussed especially at these workshops.

Your contributions are welcome!
Please visit out KEK theory group.

Purposes of J-PARC hadron physics

Understanding of strongly interacting matter
& Search for new state of matter

Quantum Chromodynamics (QCD)

- Asymptotic freedom, …
  Perturbative QCD, Parton distribution functions,
  Nucleon spin, …
- Color confinement
  Hadron spectroscopy,
  Quark-hadron matter
- Chiral symmetry
  Hadrons in nuclear medium

Haron Physics at J-PARC

Efforts are needed to get approval for projects after strangeness physics.

1st project (also ν)

- Strangeness nuclear physics (1st experiment)

Kaon and pion beams

Next projects

- Exotic hadrons
- Hadrons in nuclear medium

Proton beam

Need major upgrades

- Hard processes (50 GeV recovery)
- Nucleon spin (proton polarization)
- Quark-hadron matter (heavy ion)

My talk is mainly on hard interactions.

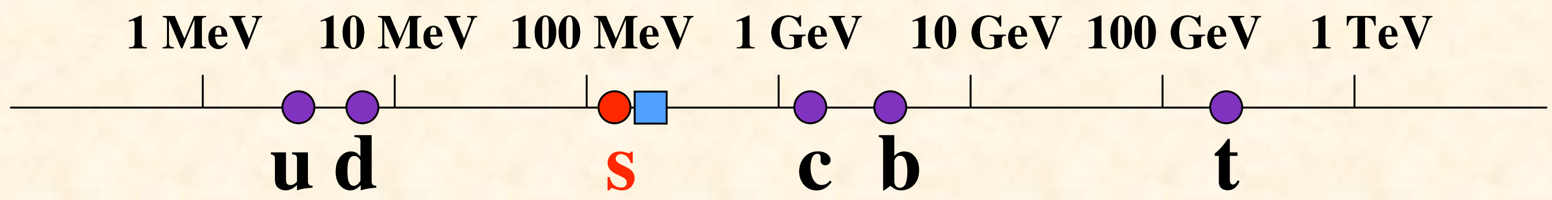
Low-Energy Hadron Physics

(I show you only a few slides on major projects.)

I skip some transparencies on low-energy physics because I should focus on hard-hadron interactions.

Strangeness in hadron physics

(1) Probe of QCD dynamics



$m_s\ \Lambda_{QCD}$

Chiral symmetry
($m \ll \Lambda_{QCD}$)

$$m_s \approx \Lambda_{QCD}$$

Non-relativistic quark model ($m \gg \Lambda_{QCD}$)

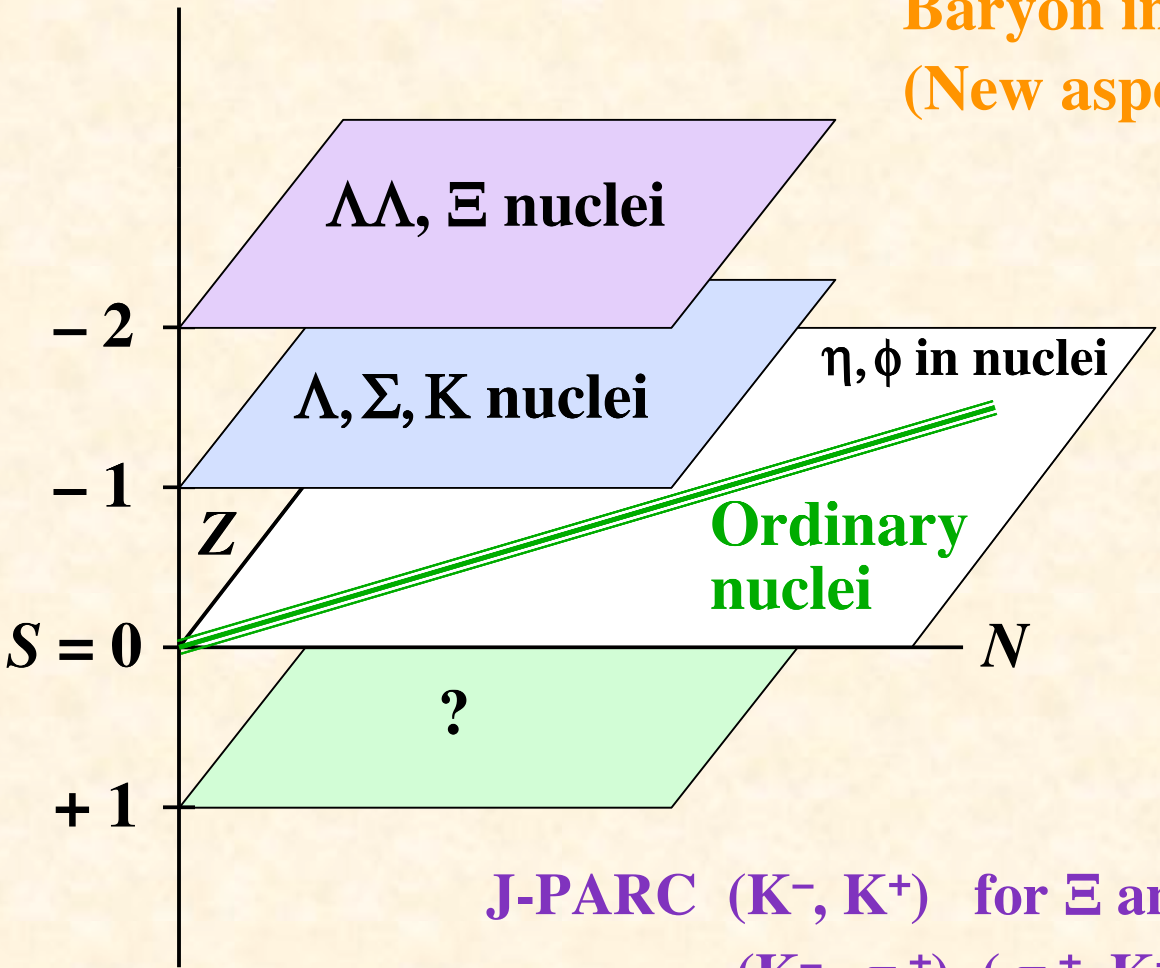
Bad point: **It is difficult to describe hadrons with strangeness.**

Good point: **Strange quark could be a good probe of QCD dynamics.**

(2) New nuclei with strangeness

New hadronic many-body system
by extending the flavor degrees of freedom.

Baryon interactions with strangeness
(New aspect of low-energy QCD)



- No data for YY interactions

- Some data for YN interactions (~ 40)

- Plenty of data for NN interactions (~ 4,000)

J-PARC (K⁻, K⁺) for Ξ and ΛΛ nuclei, YN scattering
(K⁻, $\pi^{\pm}$), ($\pi^{\pm}$, K⁺) for Λ nuclei, YN scattering

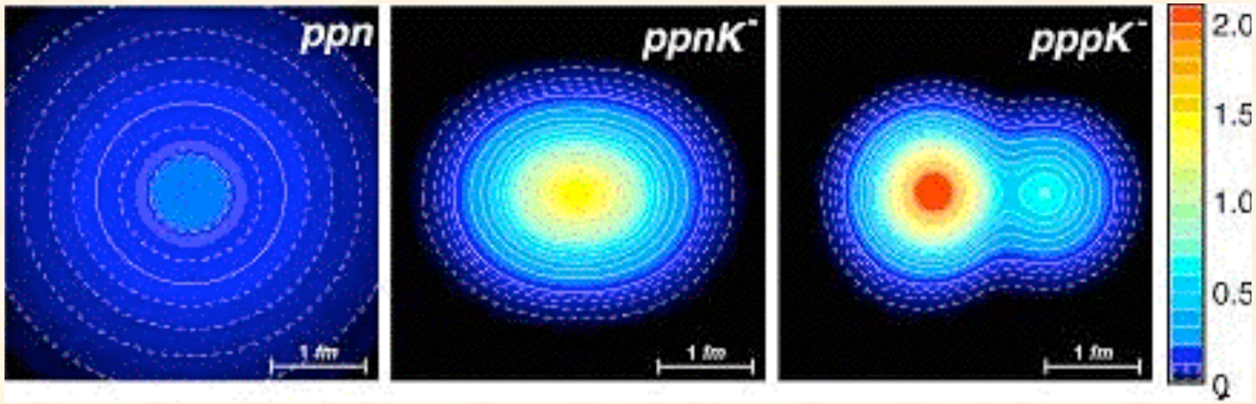
(3) Strangeness as impurity

No Pauli blocking with u, d → could penetrate deep inside a nucleus
(probe inside a nuclear medium)

New YN interactions → could lead to new forms of nuclei
(possibly high-density nuclei)

Y. Akaishi, A. Dote, T. Yamazaki,
Phys. Lett. B613 (2005) 140.
See also Phys. Rev. C70 (2004) 044313.

- 1s atomic state of kaonic hydrogen
- $\bar{K}N$ scattering analysis
- Assume: $\Lambda(1405)$ = bound state of $\bar{K}N$
  → Predictions of new kaonic nuclei



Density
($1/fm^3$)

High-Energy Hadron Physics

Introduction:

Motivations and Issues

Comments on Structure Functions I

Advantages

- **Studies of a different x region (large x) from the ones at RHIC and LHC**

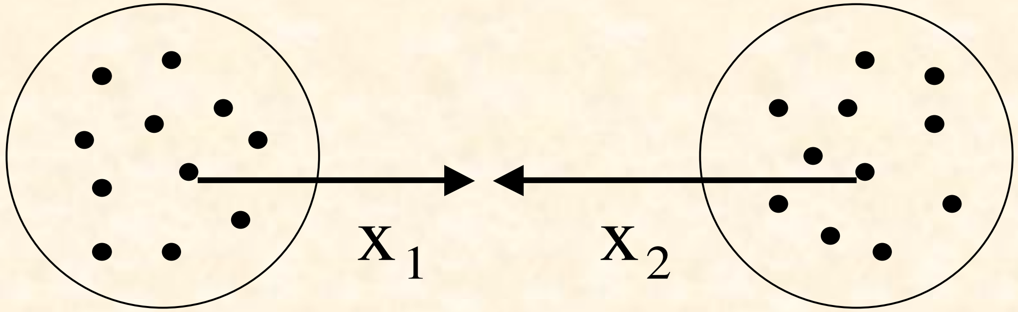
  (If the primary proton beam is polarized, there is no rival facility in the world for studying spin structure.)

- **Different observables, *e.g.* antiquark and gluon, from measurements at JLab** (which is also a large-x facility)

$\rightarrow$ **Next transparency for explanations**

- **…**

Hadron facilities



e.g. Drell-Yan: $x_1 x_2 = \frac{m_{\mu\mu}^2}{s}$

$\longrightarrow \quad x \sim \frac{\sqrt{m_{\mu\mu}^2}}{\sqrt{s}}$

$p + p(A) \to \mu^+ \mu^- + X \quad (q\bar{q} \to \mu^+ \mu^-)$

- $s = (p_1 + p_2)^2$

J-PARC: $\sqrt{s} = 10$ GeV
RHIC: $\sqrt{s} = 200$ GeV
LHC: $\sqrt{s} = 14$ TeV

- $m_{\mu\mu} \geq 3$ GeV

$x \sim \frac{\sqrt{m_{\mu\mu}^2}}{\sqrt{s}} \geq \frac{3}{10} = 0.3$ J-PARC **Large-x facility** **(Medium-x)**

$\geq \frac{3}{200} = 0.02$ RHIC

$\geq \frac{3}{14000} = 0.0002$ LHC **Small-x facility**

Comments on Structure Functions II

Advantage *and* / *or* disadvantage:

- **Perturbative QCD corrections are large.**
  - **Interesting for pQCD physicists**
  - **Can we obtain reliable parton distribution functions from measured cross sections? (→ next slides)**

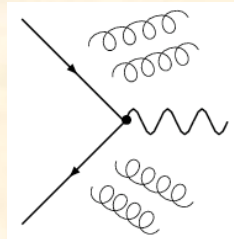
Applicability of perturbative QCD

Cross section = pQCD × non-pQCD (PDFs)

In order to extract the hadron-structure part, pQCD should be understood.

Large contributions come from the partonic threshold region

$$z = \frac{M_{\mu\mu}^{2}}{\hat{s}} \sim 1.$$



Soft-gluon resummation is needed.

Drell-Yan cross section

Ref. H. Shimizu *et al.*, PRD 71 (2005) 114007

$$\frac{\tau d\sigma}{d\tau d\phi} \sim \sum_{a,b} \int_{\tau}^{1} \frac{dx_a}{x_a} \int_{\tau/x_a}^{1} \frac{dx_b}{x_b} f_a(x_a,\mu^2) f_b(x_b,\mu^2) \omega_{ab}(z, M_{\mu\mu}^2/\mu^2, \alpha_s)$$

$$\tau = M_{\mu\mu}^2 / s, \quad z = \tau/(x_a x_b) = M_{\mu\mu}^2/\hat{s}$$

$e.g.$ in transverse spin asymmetry

$$\omega_{ab}(z, M_{\mu\mu}^2/\mu^2, \alpha_s) = \omega_{q\bar{q}}^{(0)}(z) + \frac{\alpha_s}{\pi}\omega_{q\bar{q}}^{(1)}(z, M_{\mu\mu}^2/\mu^2) + \cdots$$

$$\omega_{q\bar{q}}^{(1)}(z, M_{\mu\mu}^2/\mu^2) = C_F\left[4z\left(\frac{\ln(1-z)}{1-z}\right)_+ + \cdots\right]$$

note: large contribution from the region $z \to 1$

Mellin transformation: $\int_0^1 dx\, x^{N-1} F(x)$

$$\frac{d\sigma^N}{d\phi} \sim \sum_f f^N(\mu^2)\bar{f}^N(\mu^2)\omega^N(M_{\mu\mu}^2/\mu^2, \alpha_s)$$

$$\omega_{q\bar{q}}^{(1)N}(M_{\mu\mu}^2/\mu^2) = C_F\left[2\ln^2(Ne^{\gamma_E}) + \cdots\right]$$

A large term at $z \to 1$ corresponds to

a large term in the Mellin space at $N \to \infty$.

fixed order →

resummation ↓

LO	1	
NLO	$\alpha_s L^2$	$\alpha_s L$
⋮	⋮	⋮
N^kLO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$
	LL	NLL

$L \equiv \ln N$

Applicability of perturbative QCD in Drell-Yan

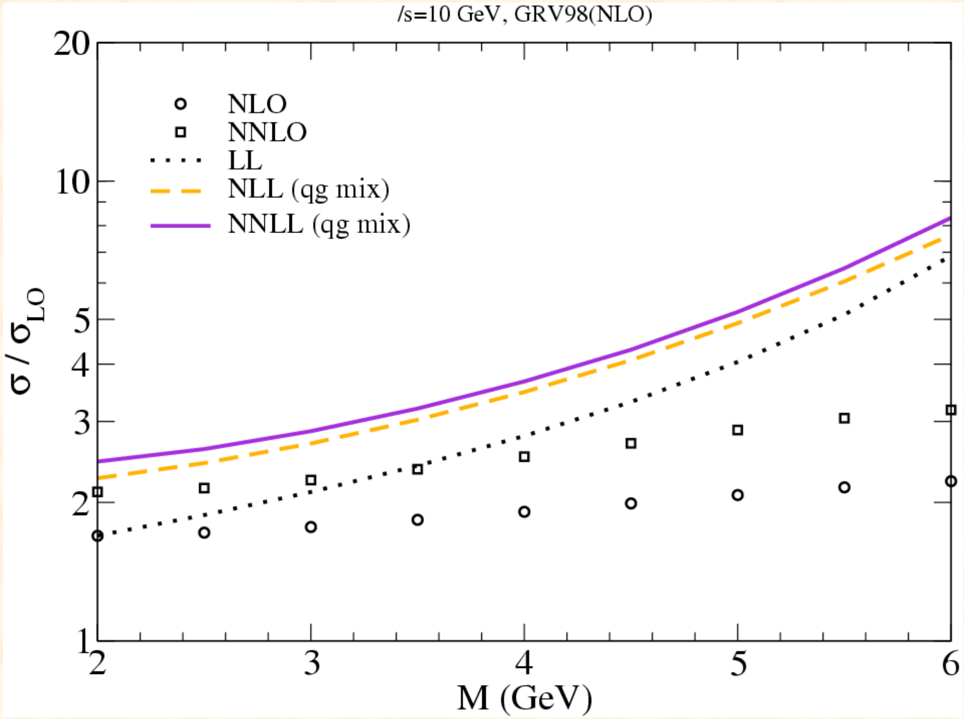
- Higher-order α_s corrections
- Resummations

pQCD corrections are shown by $\dfrac{\sigma}{\sigma_{\text{Leading Order (LO)}}}$

as a function of the dimuon mass $M_{\mu^+\mu^-}$.

Yokoya@High-energy J-PARC
http://www-conf.kek.jp/hadron08/hehp-jparc/

H. Yokoya and W. Vogelsang,
AIP Conf. Proc. 915 (2007) 595.



fixed order →

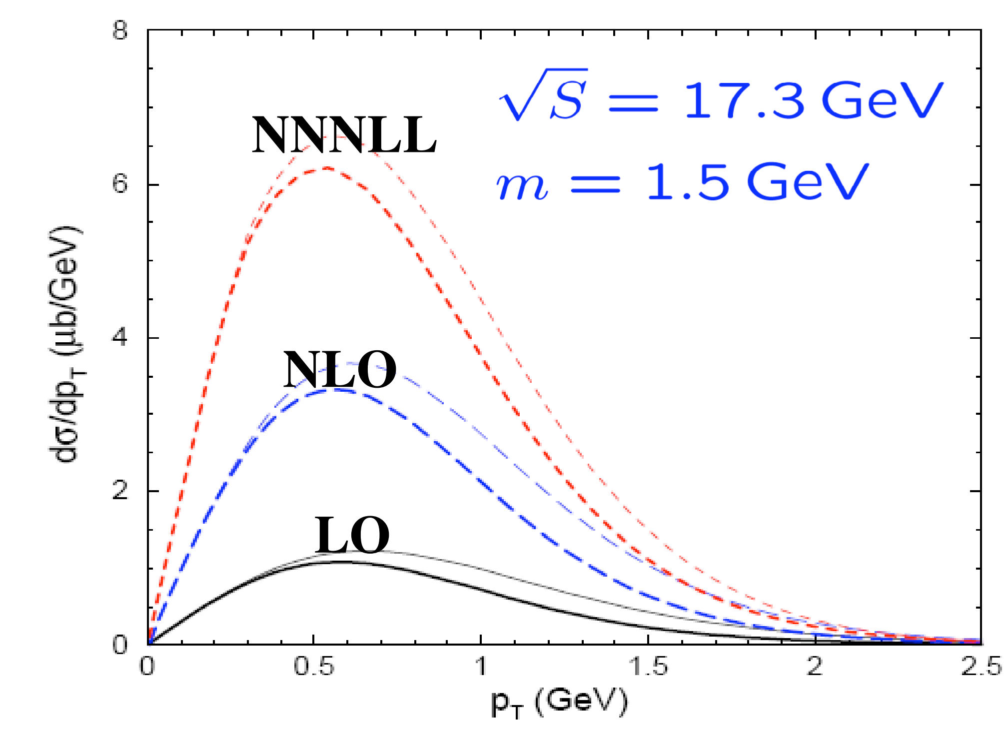
resummation ↓

LO	1	
NLO	$\alpha_s L^2$	$\alpha_s L$
	⋮	⋮
N^k LO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$
	LL	NLL

Higher-order corrections are large at J-PARC (50 GeV); however, the pQCD terms could be under control in Drell-Yan.

Applicability of perturbative QCD in charm production

N. Kidonakis, R. Vogt, Eur. Phys. J. C36 (2001) 201.



Stratmann@High-energy J-PARC
http://www-conf.kek.jp/hadron08/hehp-jparc/

J/ψ production: see Z.-B. Kang, J.-W. Qiu, AIP Conf. Proc. 1056 (2008) 170.

Higher-order corrections are larger for charm-production processes, and their convergence is not studied as the level of the Drell-Yan case.

If someone can prove that theoretical calculations converge even at 30 GeV, high-energy projects (related to any PDFs) become appropriate at J-PARC. (Very Important !!!)

Comments on Structure Functions III

Motivations and Issues:

- **Why do you need such detailed nucleon structure?**
  - **For example, the nucleon spin is one of fundamental physical quantities, but it is not understood. In order to find its origin, we need measurements from small *x* (RHIC, (LHC)) to large *x* (JLab, J-PARC).**
- **Costs for proton beamline, 50-GeV recovery, and proton-beam polarization.**

  This is nothing to do with physics, but we should propose important experiments which are worth their costs.

  - **…**

Comments on Structure Functions IV

Motivations and Issues:

- **Research purposes, Slogans for general public or at least for researchers in neighboring fields**

  - **Applications ✔ Justifiable**

    In calculating any hard interactions with a hadron, parton distribution functions are needed.
    → New physics (*e.g.* subquark, properties of quark-hadron matters, …) at RHIC and LHC.

    Possibly also to ultra-high energy cosmic rays (~10^{20} eV)
    "High-energy nuclear physics at EeV (exa 10^{18}) and ZeV (zetta 10^{21}) "

  - **Fundamentals**

    Nucleon spin, Confinement mechanism, …

  - **Appealing slogan(s)?**

    … (Ideas of young people?)

Quark substructure?

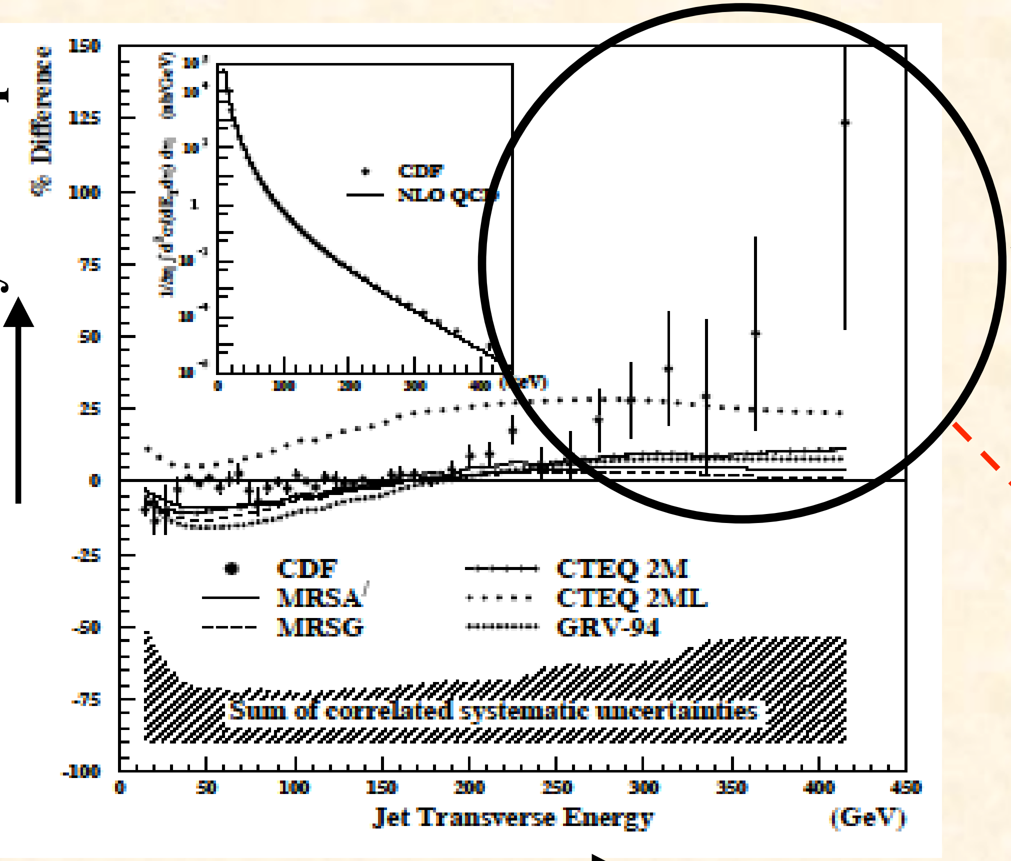
CDF experiment: PRL, 77 (1996) 438.

Comparison of theoretical calculations with CDF experimental data.

$$p + \bar{p} \rightarrow jet + X$$

$$\sqrt{s} = 1.8 \text{ TeV}, \quad E_T^{jet} = 15 - 400 \text{ GeV}$$

Difference between theory and experiment



Jet transverse energy

Subquark signature ???

The same thing could happen at LHC.

Could be explained without substructure

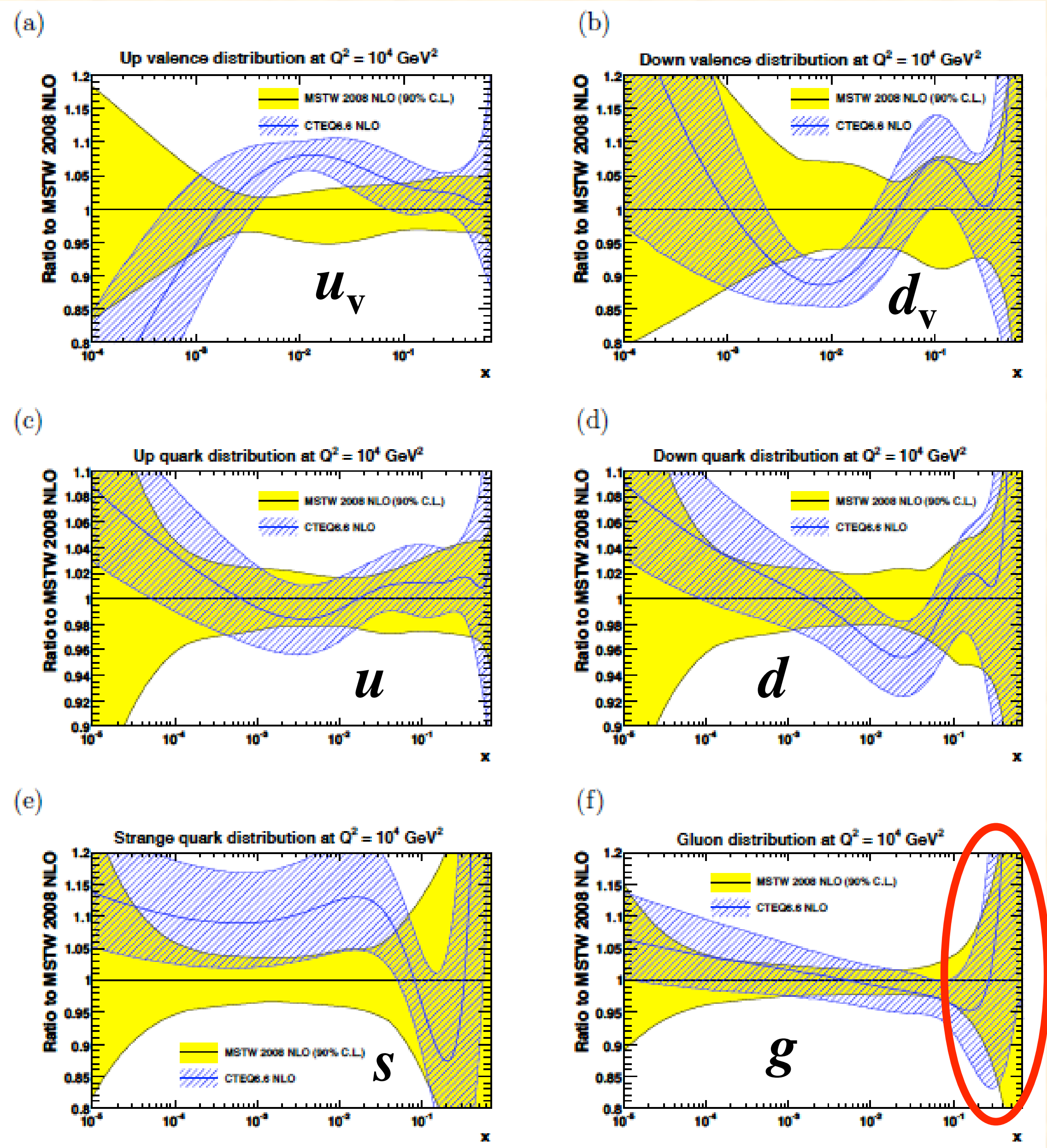
(importance of accurate PDFs)

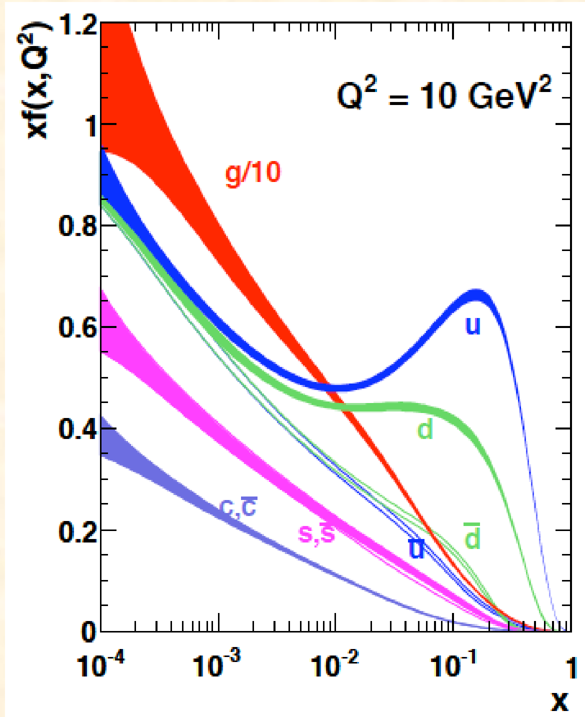
PDF uncertainty

A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, arXiv: 0901.0002.

MSTW

CTEQ6.6





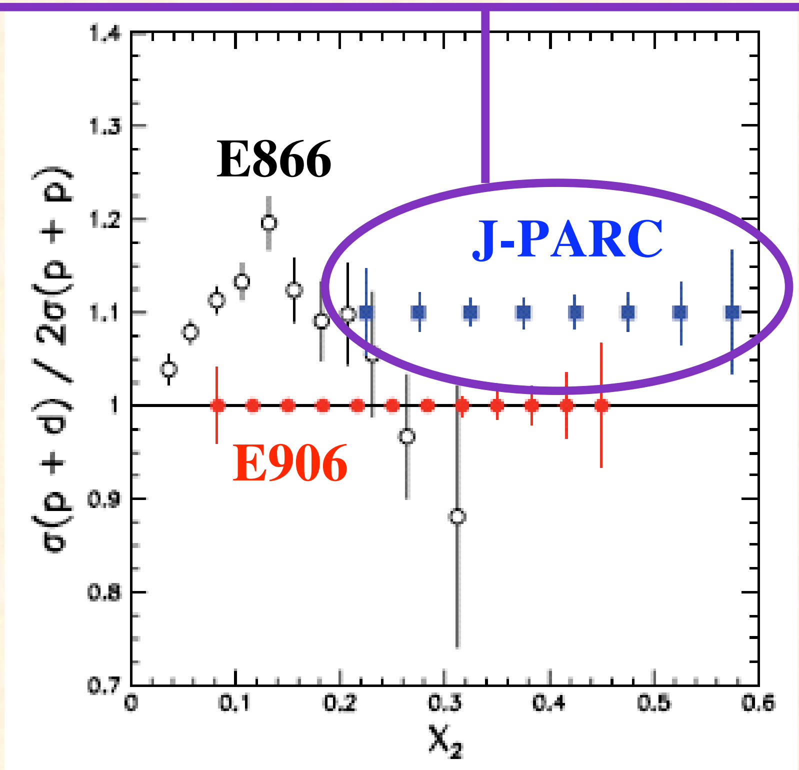
Important x region for finding an "exotic event" in a high-p_T region at LHC.

J-PARC x region

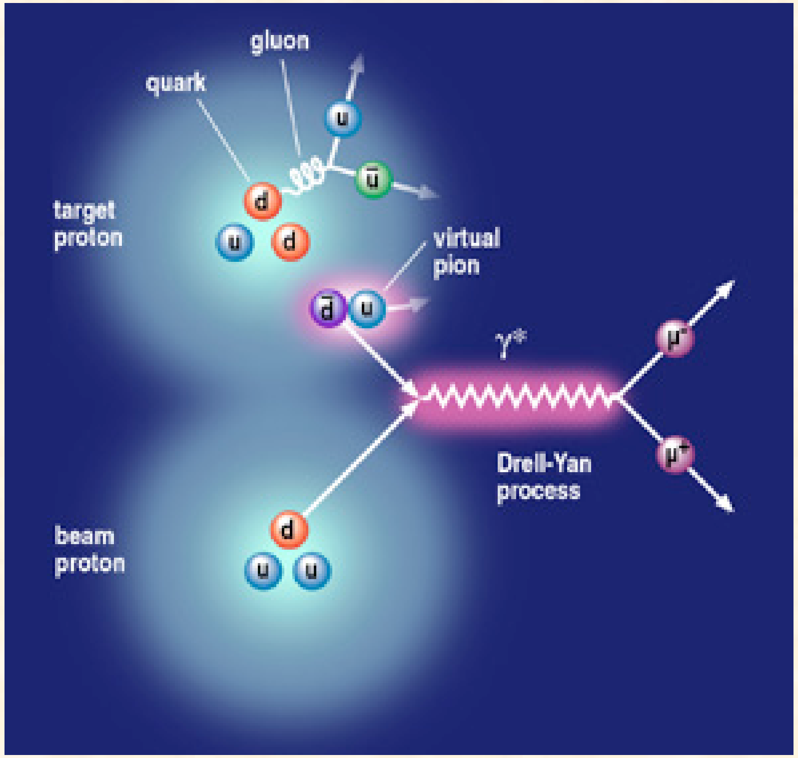
Possible Topics I

Flavor asymmetric antiquark distributions: $\bar{u} / \bar{d}$

Theoretical studies are needed for physics importance in this *x* region.



J-PARC proposal (P24), M. Bai *et al.* (2007)



http://www.acuonline.edu/academics/cas/physics/research/e906.html

This project is suitable for probing "peripheral structure" of the nucleon.

Refs. SK, Phys. Rep. 303 (1998) 183;
G. T. Garvey and J.-C. Peng, Prog. Part. Nucl. Phys. 47 (2001) 203.

Spin asymmetry in elastic scattering

Single spin asymmetry

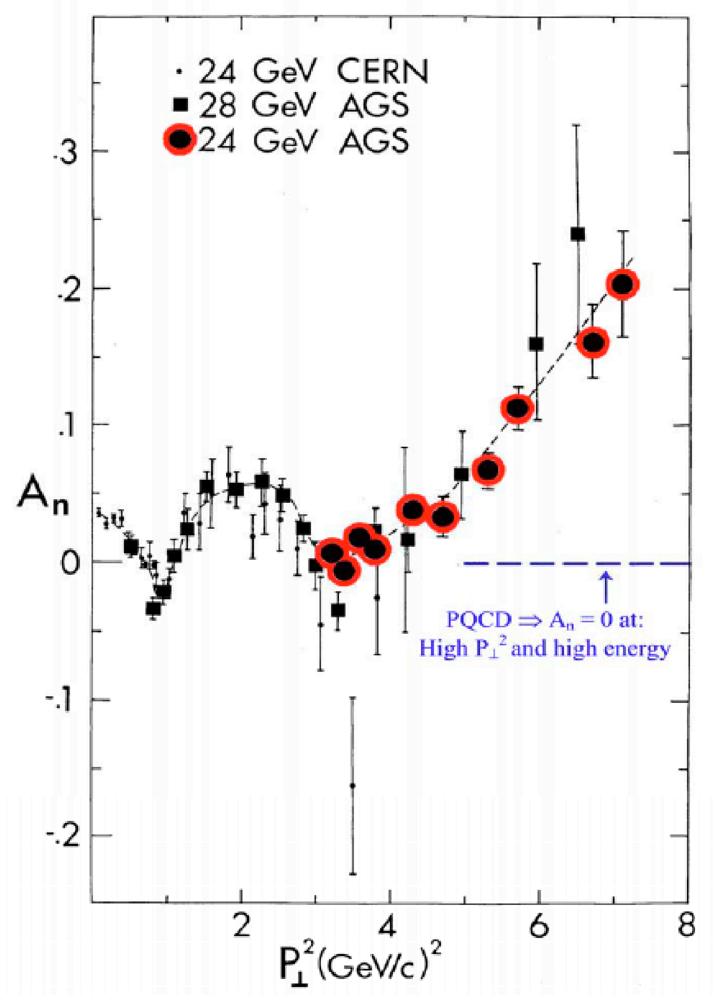
$$A_n = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- J-PARC 30 GeV is the same as the AGS energy. (Kinematical range is similar.)

  Simply the AGS type measurements do not have physics impact.

For a possible J-PARC experiment,

- New observable should be investigated for providing a clue to pin down a possible mechanism of producing the asymmetry at large p_T.
- Suggestions from theorists?



Krisch@Riken-J-PARC08

D. G. Crabb et al., PRL65 (1990) 3241

Possibilities are discussed in the proposal P24 (Y. Goto *et al.*)

Proposal P24: Polarized proton acceleration at J-PARC

Proposal

Polarized Proton Acceleration at J-PARC

November 30, 2007

M. Bai[1], M. Brooks[5], J. Chiba[11], N. Doshita[12], Y. Fukao[7], Y. Goto[7,8†], M. Grosse Perdekamp[2], K. Hatanaka[6], H. Huang[1], K. Imai[4], T. Iwata[12], S. Ishimoto[3], X. Jiang[5], K. Kondo[12], G. Kunde[5], K. Kurita[9], M. J. Leitch[5], M. X. Liu[5], A. U. Luccio[1], P. L. McGaughey[5], A. Molodojentsev[3], C. Ohmori[3], J.-C. Peng[2], T. Roser[1], N. Saito[3], H. Sato[3†], S. Sawada[3], R. Seidl[2], T.-A. Shibata[10], J. Takano[3], A. Taketani[7,8], M. Togawa[8], and A. Zelenski[1]

[1] *Brookhaven National Laboratory, Upton, NY 11973, USA*
[2] *University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[3] *KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan*
[4] *Kyoto University, Kyoto 606-8502, Japan*
[5] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[6] *Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*
[7] *RIKEN, Institute of Physical and Chemical Research, Wako, Saitama 351-0198, Japan*
[8] *RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*
[9] *Rikkyo University, Tokyo 171-8501, Japan*
[10] *Tokyo Institute of Technology, Tokyo 152-8551, Japan*
[11] *Tokyo University of Science, Noda, Chiba 278-8510, Japan*
[12] *Yamagata University, Yamagata 990-8560, Japan*

I introduce some topics from this proposal, but please look at this proposal for technical details of the beam polarization and physics topics.

Primary-proton-beam polarization

Proposal P24: Polarized proton acceleration at J-PARC

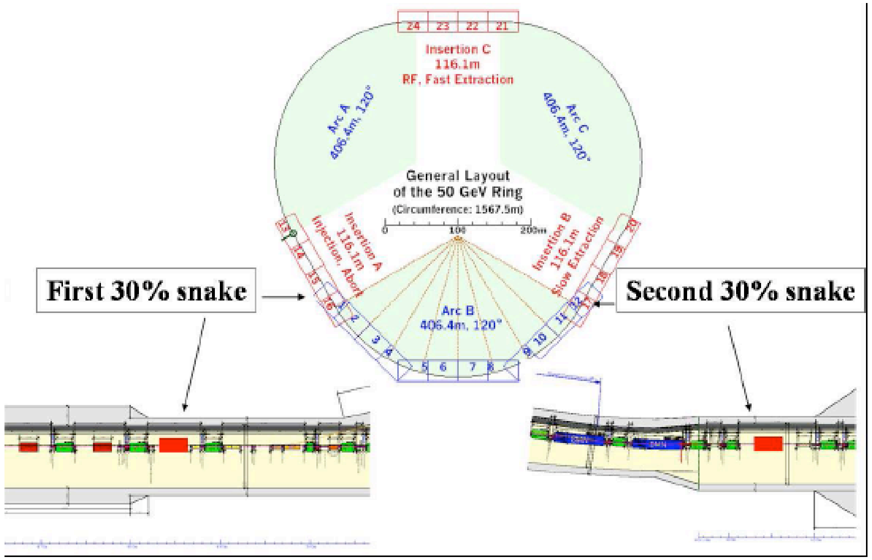


Figure 16: Possible location of partial helical snake magnets in the MR.

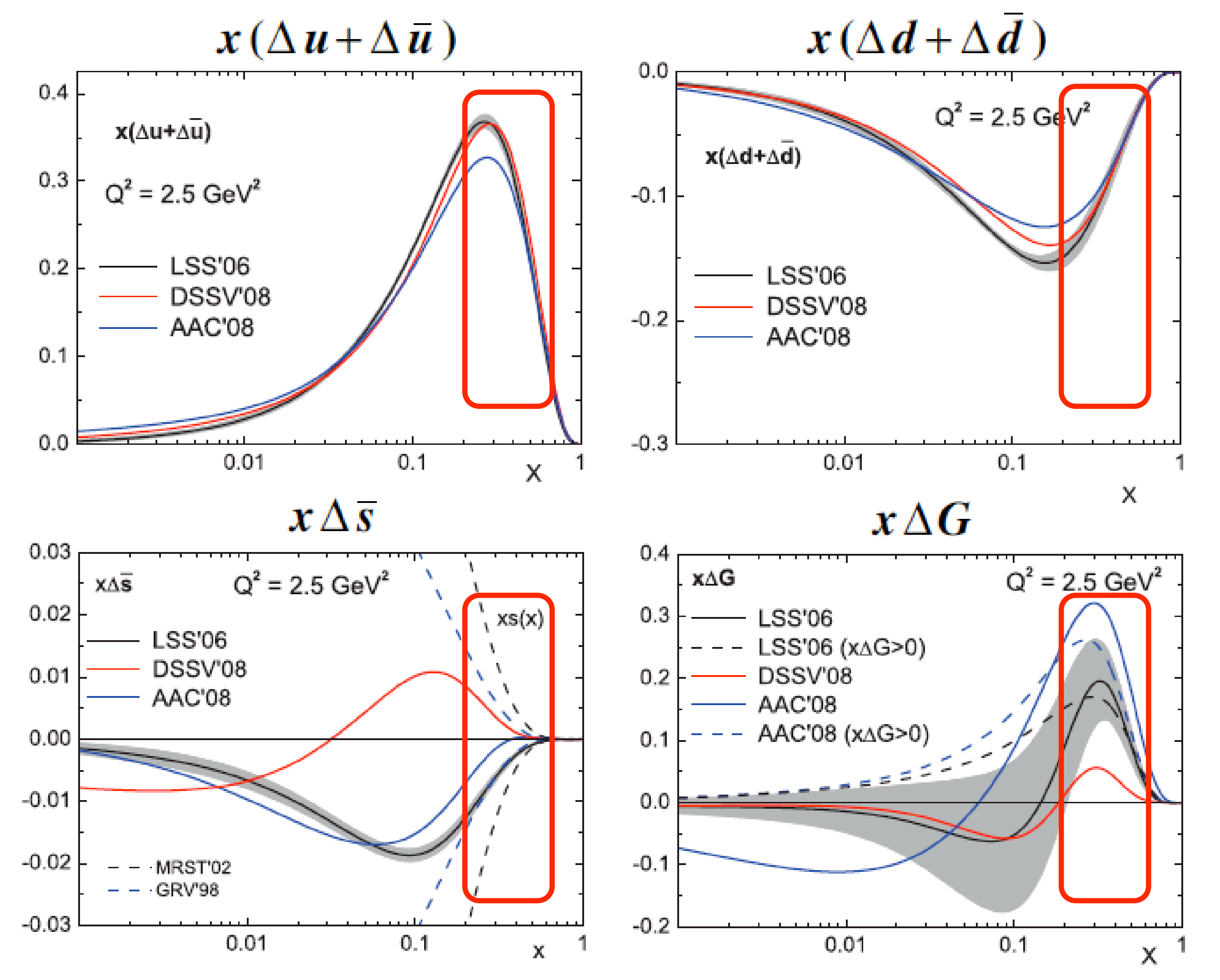
Item	Cost (million yen)
Polarized ion source	200
Source to RCS	50
Polarization in RCS	100
Polarized beam in MR	500
Primary beam extraction	250
pC polarimeter	100
Absolute polarimeter	100 - 300
Total	1,300 - 1,500

Table 1: Rough cost estimation for the polarized proton acceleration at J-PARC.

The proton beam polarization is technically possible.

Situation of polarized PDFs

S. E. Kuhn, J.-P. Chen, and E. Leader,
arXiv:0812.3535 [hep-ph],
to be published in Prog. Part. Nucl. Phys.



J-PARC kinematical range

Gluon and antiquark distributions have large uncertainties.

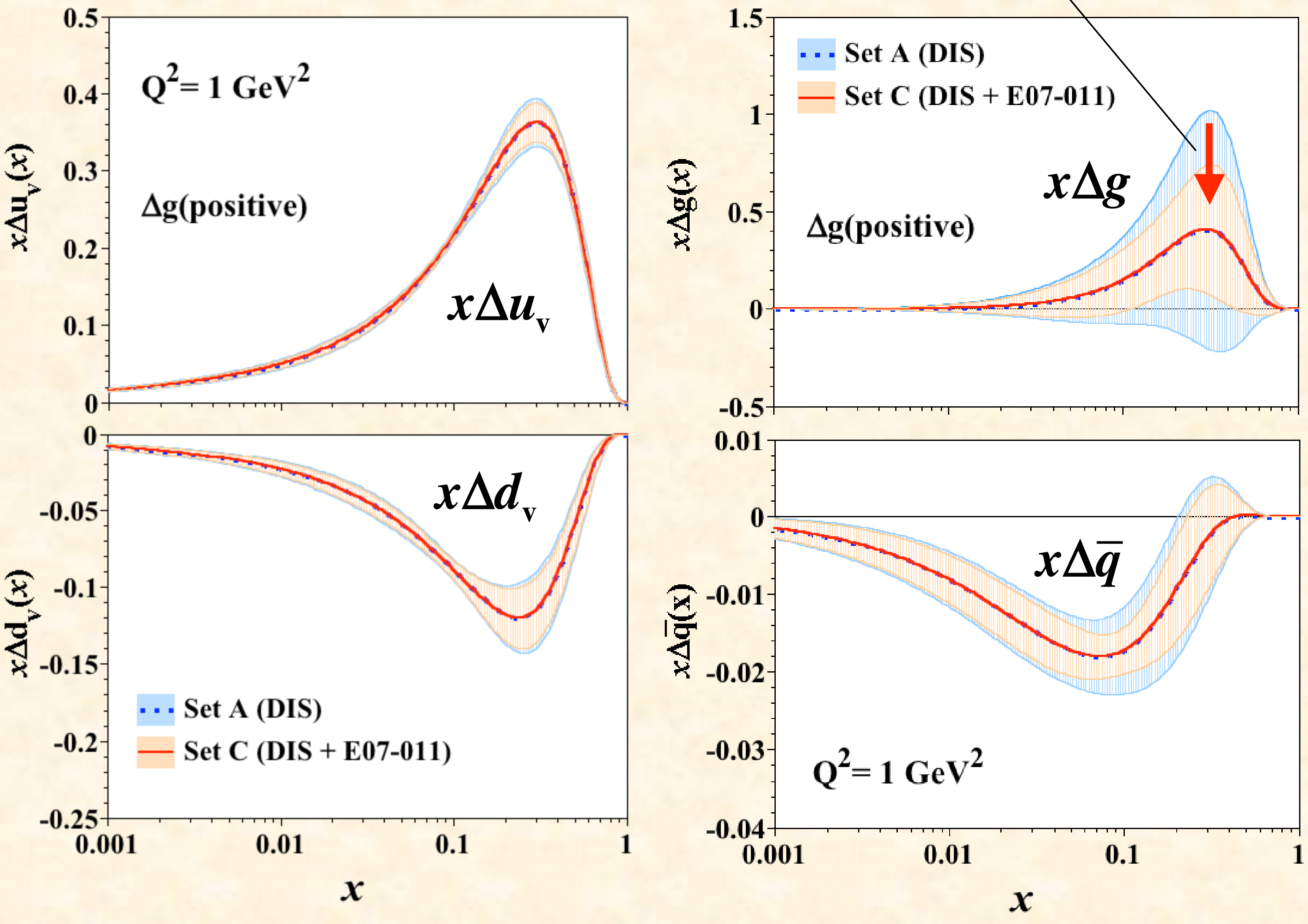
Comments on AAC08 polarized PDFs

Determination of gluon polarization
from deep inelastic scattering and collider data,
M. Hirai and S. Kumano,
Nucl. Phys. B813 (2009) 106.

Effects of future JLab E07-011 data

It is interesting to find the reduction of Δg uncertainties by the lepton scattering (JLab E07-011) data.

The same effect is expected at future EIC.



A: Current DIS data
C: Current DIS data + E07-011

Reason for the reduction of Δg uncertainty

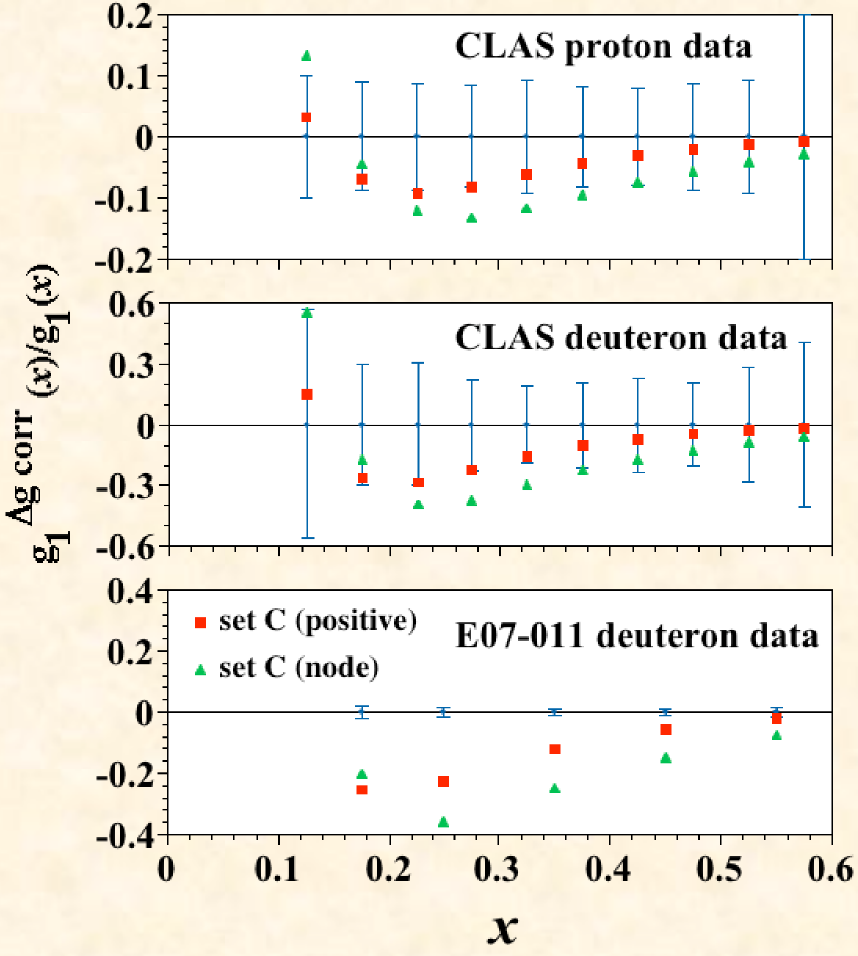


FIG. 8: The ratio of the gluon NLO-correction term to the polarized structure function $g_1(x, Q^2)$ in Eq. (5). It is compared with experimental errors, which are shown by the ratio $\delta g_1(x, Q^2)/g_1(x, Q^2)$ in Eq. (6).

Two possibilities:

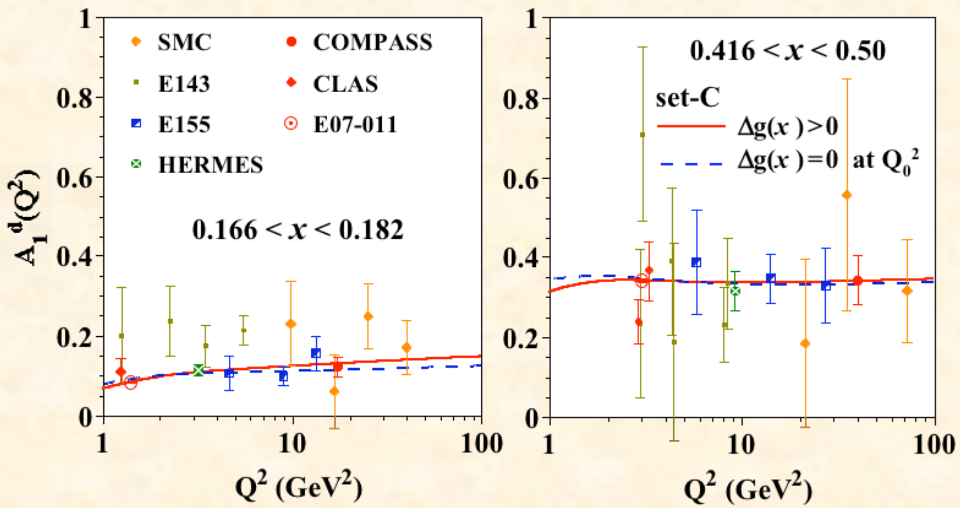
(1) Error correlation between antiquark and gluon distributions (but note antiquark reduction is smaller).

(2) Gluonic NLO term in g_1 (left figures).

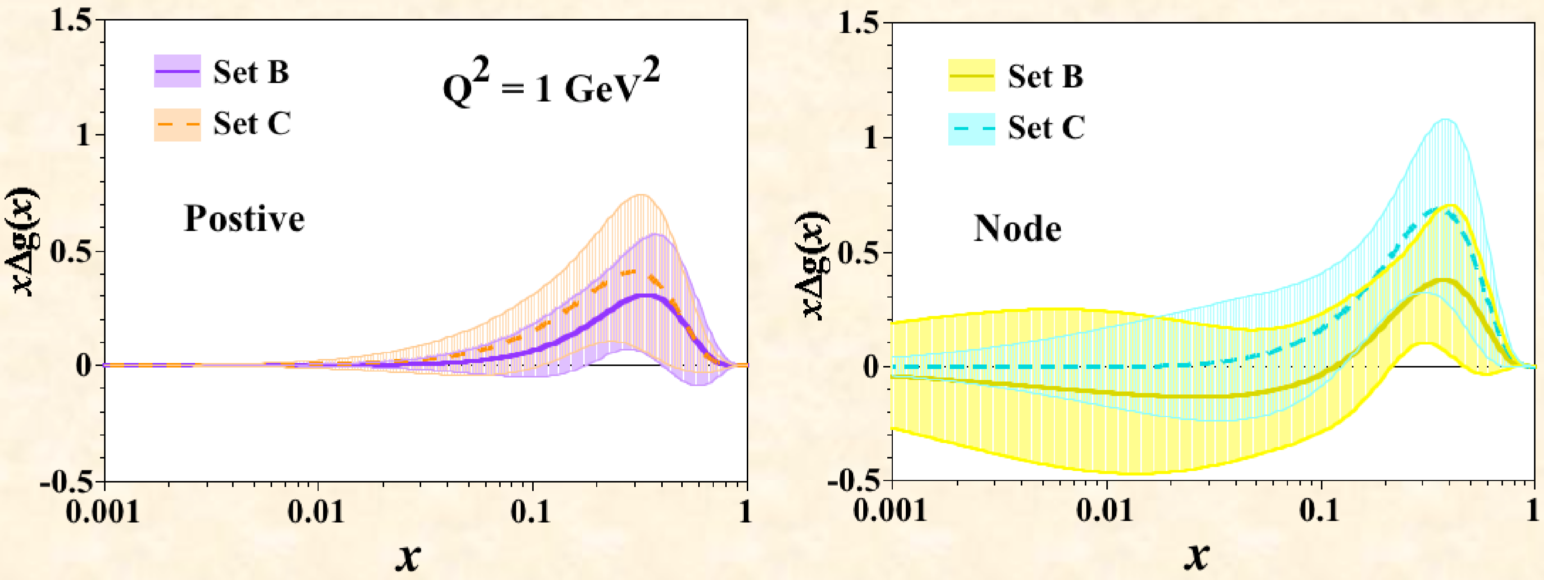
$$\frac{1}{g_1(x,Q^2)}\frac{1}{2}\sum_{i=1}^{n_f} e_i^2 \int_x^1 \frac{dz}{z}\Delta C_g(x/z,Q^2)\Delta g(z,Q^2), \quad (5)$$

CLAS data are not accurate enough to probe the gluonic NLO term, but E07-011 data are so accurate that Δg is restricted through the NLO term in g_1.

Q^2 dependence is not the reason for the reduction according to the figure below.



$\Delta g(x)$ with PHENIX run-5 or JLab E07-011 data



B: Current DIS data
+ RHIC-π^0 (run-5)
C: Current DIS data
+ E07-011

Δg function	First moment	DIS	DIS+RHIC π	DIS+E07-011
positive	Δg	0.53	0.36	0.53
positive	$\delta(\Delta g)$	0.72	0.26	0.38
positive	$\delta(\Delta g)/\Delta g$	1.36	0.71	0.73
node	Δg	0.87	0.4	0.87
node	$\delta(\Delta g)$	0.89	0.31	0.47
node	$\delta(\Delta g)/\Delta g$	1.02	0.77	0.54

Significant improvements

JLab-E07-011 is comparable to RHIC run-5 π^0 in determining $\Delta g(x)$.

Return to possible J-PARC projects

Single spin asymmetry

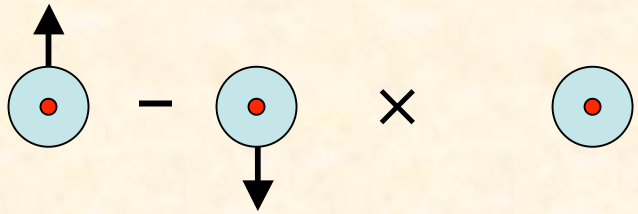
(No polarized proton beam is needed!)

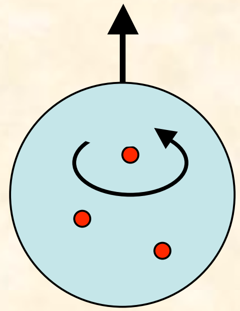
- Sivers effect

Nucleon Quark

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$$A_N \sim f_{1T}^{\perp} \cdot D_1 \quad \text{(Sivers function} \times \text{Unpolarized fragmentation)}$$





Burkardt @J-PARC-HS05

Probe of angular momentum

The Sivers function describes unpolarized quark in the transversely polarized nucleon.

- Collins effect

$$A_N \sim \delta_T q \cdot H_1^{\perp} \quad \text{(Transversity} \times \text{Collins fragmentation function)}$$

The transversity distribution describes transverse quark polarization in the transversely polarized nucleon.

The Collins fragmentation function describes a fragmentation of polarized quark into unpolarized hadron.

- Higher-twist

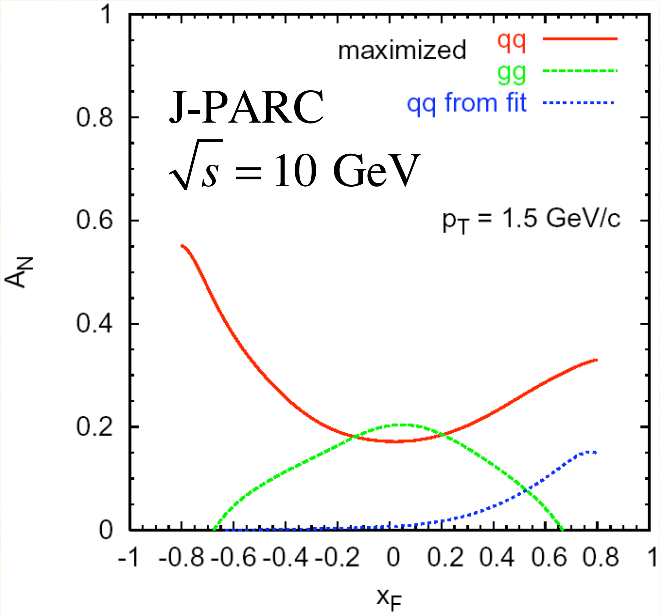
Qiu, Sterman; Koike@J-PARC-HS05

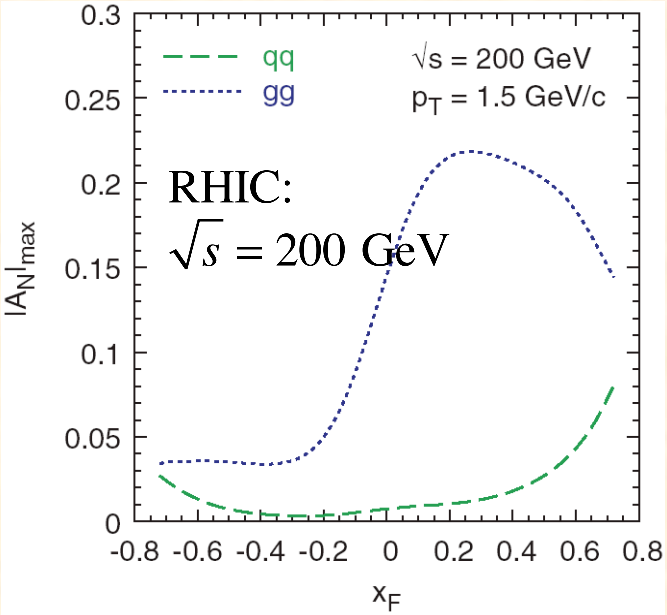
Single spin asymmetry

D-meson production

$$gg \to c\bar{c}, \quad q\bar{q} \to c\bar{c}$$

$\to c$ & $\bar{c}$ **are not polarized (no Collins mechanism)**





Y. Goto @J-PARC-HS05

U. D'Alesio @BNL, 2005

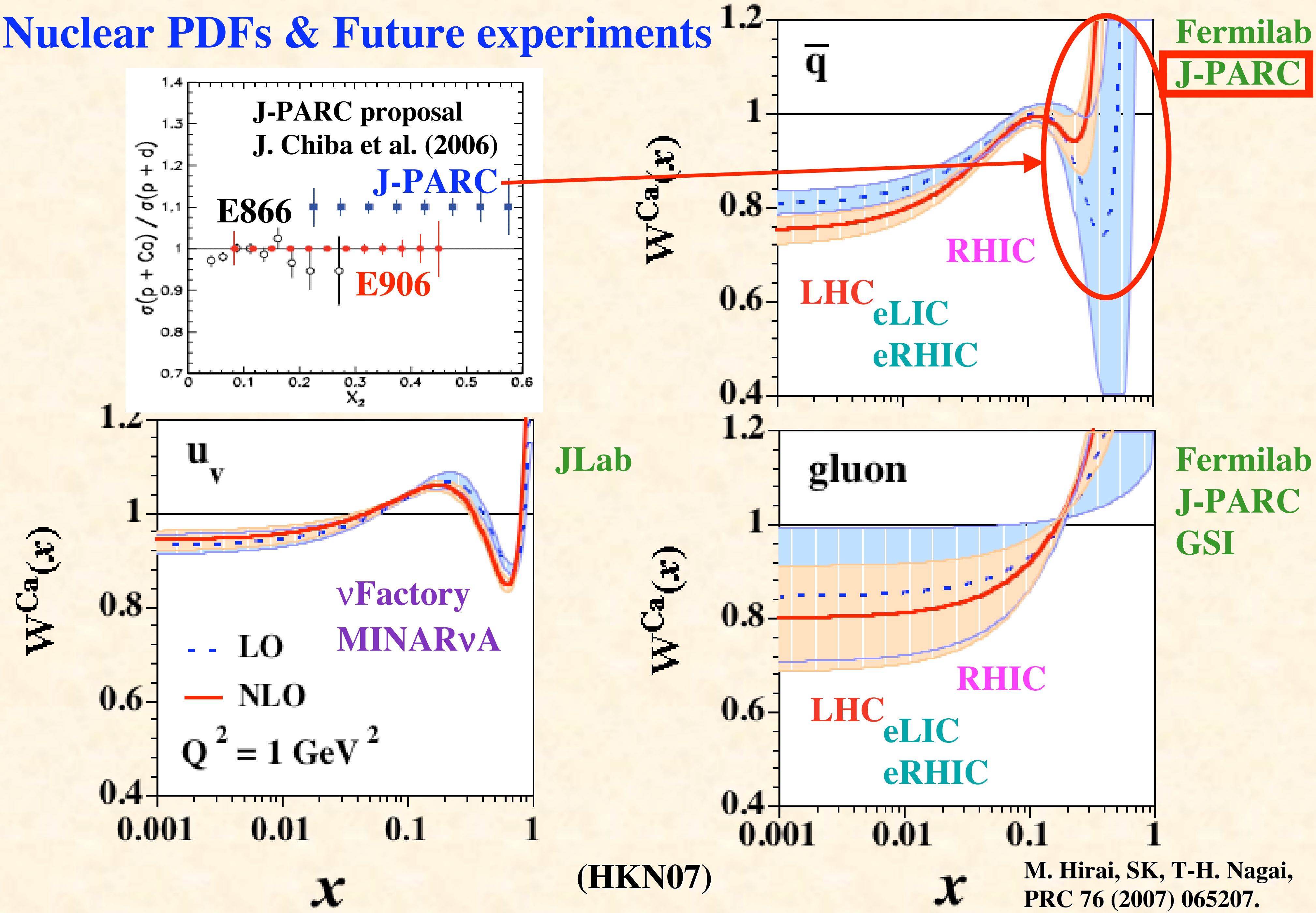
M. Anselmino *et al.*, PRD 70 (2004) 074025.

In the region $x_F < 0$

J-PARC: sensitive to quark Sivers effect

RHIC: sensitive to gluon Sivers effect

Nuclear PDFs & Future experiments



M. Hirai, SK, T-H. Nagai,
PRC 76 (2007) 065207.

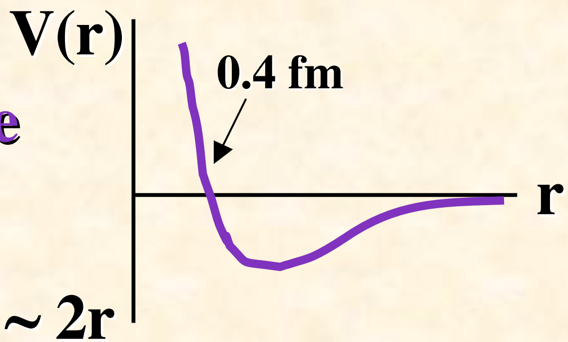
Short-range NN interaction

Ciofi degli Atti@J-PARC-NP07

Strikman@INPC07

E. Piasetzky et al.,
PRL97 (2006) 162504

- Short-range repulsive core, Tensor force
- Quark degrees of freedom
- Cold dense nuclear matter, Neutron star



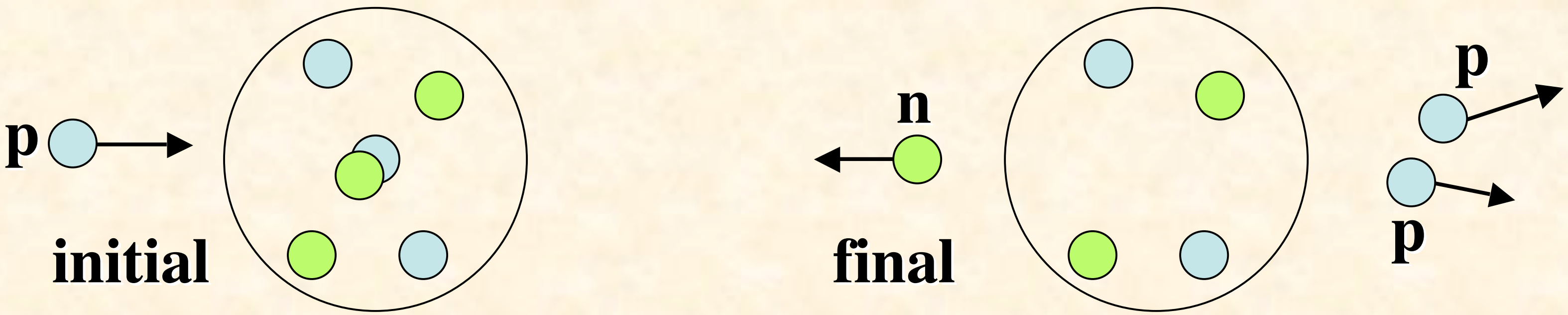
Nuclei do not collapse → Short-range repulsive core

Nucleon size r ≈ 0.8 fm

Average nucleon separation in a nucleus: R ≈ 2 fm ~ 2r

→The short-range part is important as the density becomes larger (neutron star).

A(p, 2pN)X experiment for short range correlation



Color Transparency

"Probe of dynamics of elementary reactions"

At large momentum transfer, a small-size component of the hadron wave function should dominate. This small-size hadron could freely pass through nuclear medium. (Transparent)

Investigate $p\,A \rightarrow p\,p\,(A\text{-}1)$

Nuclear transparency: $T = \dfrac{\sigma_A}{A\sigma_N}$

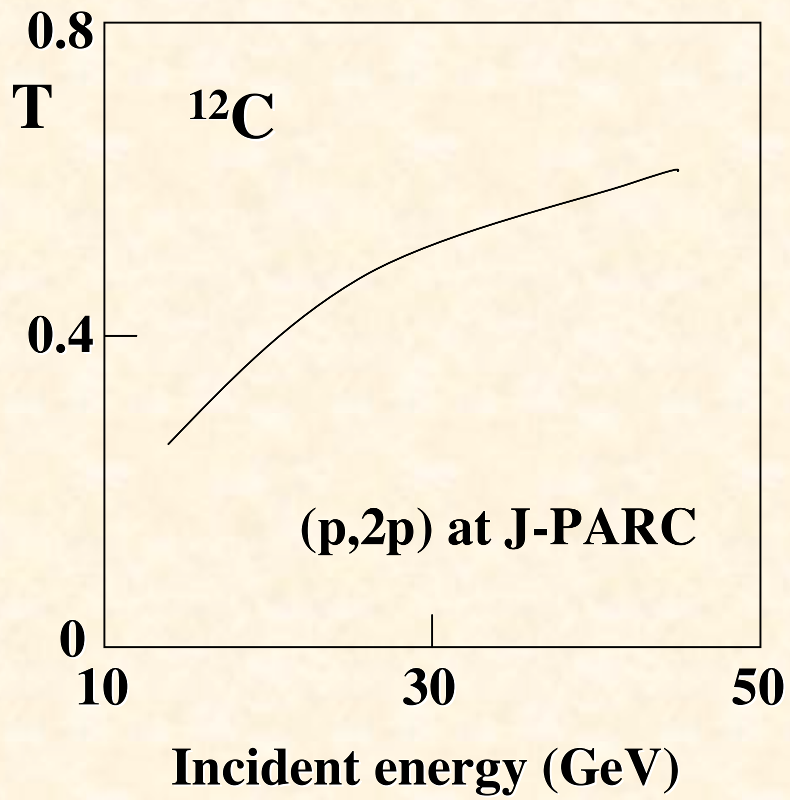
Hadron size ~ 1 / hard scale

Color transparency:

$T \rightarrow$ larger, as the hard scale $\rightarrow$ larger

(BNL-EVA) J. Aclander et al., PRC 70 (2004) 015208

Possibility at J-PARC



Possible Topics II

(closely related to my studies)

Structure of Spin-1 Hadrons

Note: Proton-beam polarization is not needed.
Polarized deuteron target is enough at J-PARC!

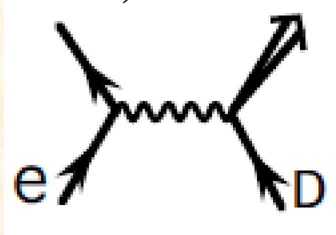
Tensor Structure in High-energy Reactions

(Note: No polarized proton beam is needed!)

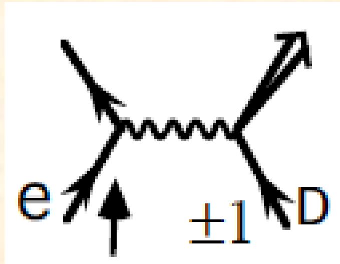
L. L. Frankfurt and M. I. Strikman, NP A405 (1983) 557.
P. Hoodbhoy, R. L. Jaffe, and A. Manohar, NP B312 (1989) 571.

Structure Functions
(in e scattering)

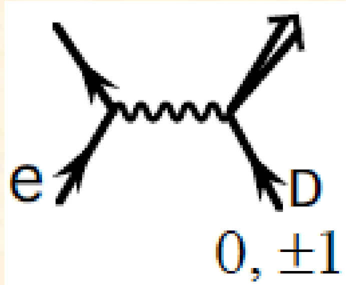
$$F_1 \propto \langle d\sigma \rangle$$



$$g_1 \propto d\sigma(\uparrow, +1) - d\sigma(\uparrow, -1)$$



$$b_1 \propto d\sigma(0) - \frac{d\sigma(+1) + d\sigma(-1)}{2}$$



Parton Model

$$F_1 = \frac{1}{2}\sum_i e_i^2 (q_i + \bar{q}_i) \qquad q_i = \frac{1}{3}(q_i^{+1} + q_i^{0} + q_i^{-1})$$

$$\left[q_\uparrow^H(x, Q^2)\right]$$

Unpolarized quark distribution in a spin-1 hadron.

$$g_1 = \frac{1}{2}\sum e_i^2 (\Delta q_i + \Delta\bar{q}_i) \qquad \Delta q_i = q_{i\uparrow}^{+1} - q_{i\downarrow}^{+1}$$

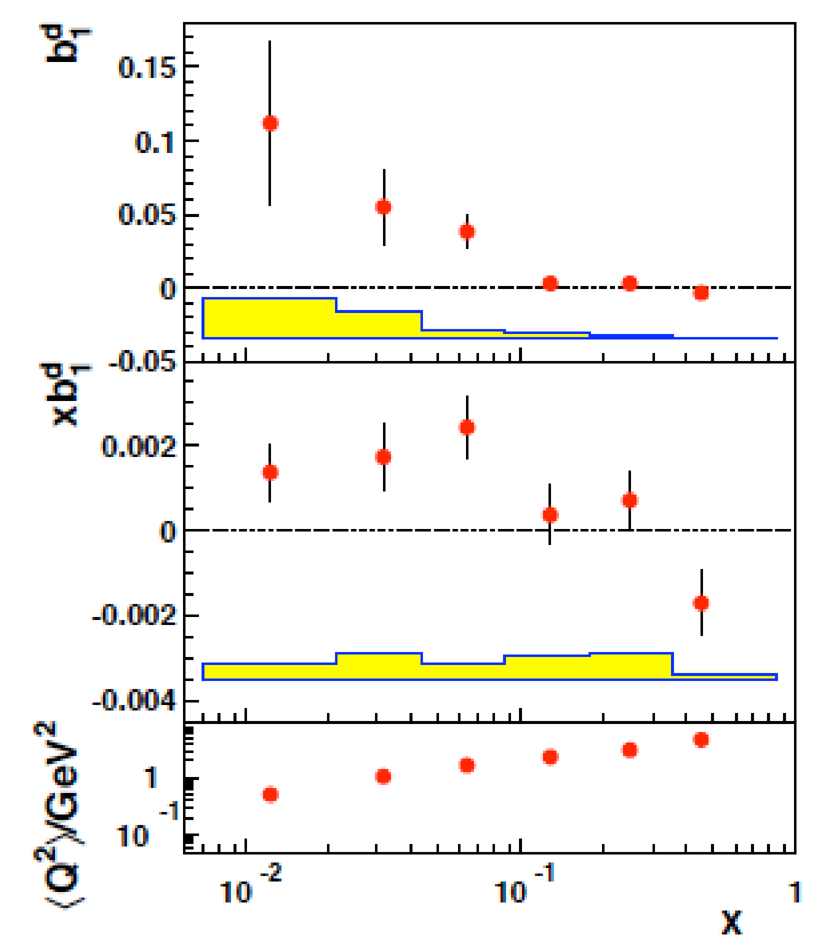
$$b_1 = \frac{1}{2}\sum_i e_i^2 (\delta q_i + \delta\bar{q}_i) \qquad \delta q_i = q_i^{0} - \frac{q_i^{+1} + q_i^{-1}}{2}$$

HERMES results on b_1

A. Airapetian *et al.*, PRL 95 (2005) 242001

27.6 GeV/c $\rightleftarrows$, 0

positron **deuteron**



b_1 measurement in the kinematical region

$0.01 < x < 0.45, \;\; 0.5 \text{ GeV}^2 < Q^2 < 5 \text{ GeV}^2$

b_1 sum rule

$$\int_{0.002}^{0.85} dx\, b_1(x) = [1.05 \pm 0.34(\text{stat}) \pm 0.35(\text{sys})] \times 10^{-2}$$

at $Q^2 = 5 \text{ GeV}^2$

In the restricted Q^2 range $Q^2 > 1 \text{ GeV}^2$

$$\int_{0.02}^{0.85} dx\, b_1(x) = [0.35 \pm 0.10(\text{stat}) \pm 0.18(\text{sys})] \times 10^{-2}$$

at $Q^2 = 5 \text{ GeV}^2$

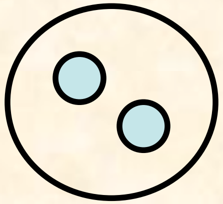
Electric quadrupole form factor

F. E. Close and SK, PRD42, 2377 (1990)

$$\int dx\, b_1^D(x) = \lim_{t \to 0} -\frac{5}{12}\frac{t}{M^2} F_Q(t) + \frac{1}{9}\left(\delta Q + \delta \overline{Q}\right)_{\text{sea}} \Rightarrow 0$$

Tensor Structure in Proton-Deuteron Drell-Yan

b_1 for spin-1 particles **(Note: No polarized proton beam is needed!)**



only in S-wave **$b_1 = 0$**

1st measurement of b_1:
(HERMES) A. Airapetian et al.,
PRL 95 (2005) 242001.

Polarized proton-deuteron Drell-Yan
(Theory) S. Hino and SK,
PR D 59 (1999) 094026,
D 60 (1999) 054018.
(Experiment) None → J-PARC

Spin asymmetries

$$A_{LL} = \frac{\sum_a e_a^2 \left[\Delta q_a(x_A) \Delta \bar{q}_a(x_B) + \Delta \bar{q}_a(x_A) \Delta q_a(x_B) \right]}{\sum_a e_a^2 \left[q_a(x_A) \bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B) \right]}$$

$$A_{TT} = \frac{\sin^2\theta \cos(2\phi)}{1+\cos^2\theta} \frac{\sum_a e_a^2 \left[\Delta_T q_a(x_A) \Delta_T \bar{q}_a(x_B) + \Delta_T \bar{q}_a(x_A) \Delta_T q_a(x_B) \right]}{\sum_a e_a^2 \left[q_a(x_A) \bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B) \right]}$$

$$\delta q_i = q_i^{\,0} - \frac{q_i^{\,+1} + q_i^{\,-1}}{2}$$

Note: $\delta \neq$ transversity in my notation

$$A_{UQ_0} = \frac{\sum_a e_a^2 \left[q_a(x_A) \delta \bar{q}_a(x_B) + \bar{q}_a(x_A) \delta q_a(x_B) \right]}{\sum_a e_a^2 \left[q_a(x_A) \bar{q}_a(x_B) + \bar{q}_a(x_A) q_a(x_B) \right]}$$

Unpolarized proton
+ Tensor polarized deuteron

***Unique* advantage of J-PARC ($\delta \bar{q}$ measurement)**

$$\int dx\, b_1^D(x) = 0 + \frac{1}{9}\left(\delta Q + \delta \bar{Q}\right)_{\text{sea}}$$

$$A_{UQ_0}(\text{large } x_F) \approx \frac{\sum_a e_a^2 q_a(x_A) \delta \bar{q}_a(x_B)}{\sum_a e_a^2 q_a(x_A) \bar{q}_a(x_B)}$$

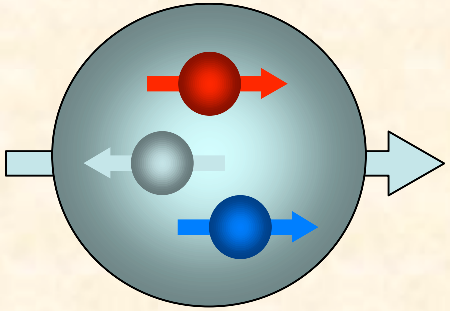
F. E. Close and SK, PRD42, 2377 (1990)

Gottfried: $\displaystyle \int \frac{dx}{x}\left[F_2^p(x) - F_2^n(x) \right] = \frac{1}{3} + \frac{2}{3}\int dx \left[\bar{u} - \bar{d} \right]$

Generalized Parton Distributions at Hadron Facilities (J-PARC, GSI, …)

Ref. Novel two-to-three hard hadronic processes and possible studies of generalized parton distributions at hadron facilities, SK, M. Strikman, K. Sudoh, arXiv:0905.1453 [hep-ph].

Nucleon Spin



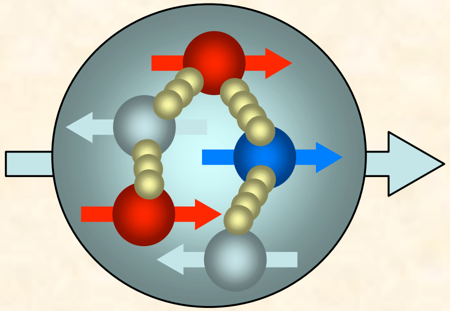
Naïve Quark Model

$\Delta\Sigma = \Delta u_v + \Delta d_v = 1$

Electron / muon scattering

$\Delta\Sigma \approx 0.1 \sim 0.3$

Almost none of nucleon spin is carried by quarks!



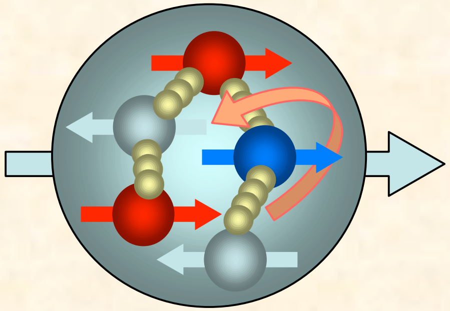
QCD

Sea-quarks and gluons?

Gluon: ΔG

Sea-quarks: Δq_{sea}

Recent data indicate ΔG is small at $x \sim 0.1$.



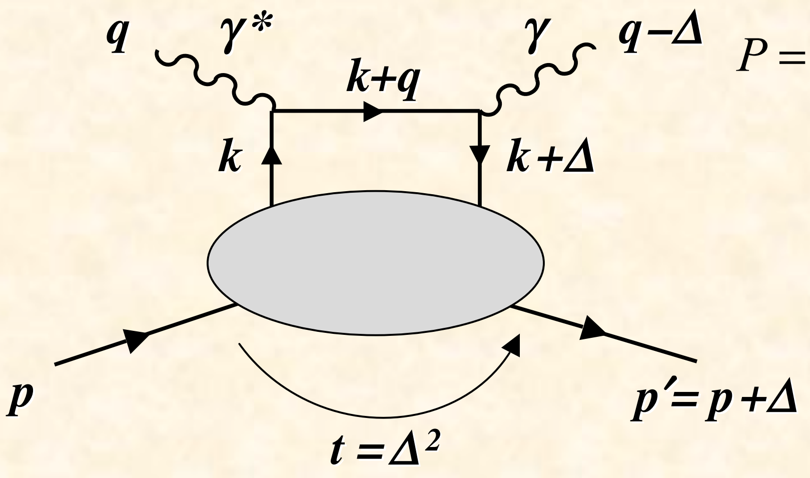
Orbital angular momenta ?

L_q, L_g

Future experiments

Nucleon Spin: $$\frac{1}{2} = \frac{1}{2}\underbrace{\left(\Delta u_v + \Delta d_v + \Delta q_{sea}\right)}_{\Delta\Sigma} + \Delta G + L_q + L_g$$

Generalized Parton Distributions (GPDs)



$$P=\frac{p+p'}{2},\ \ \Delta=p'-p$$

GPDs are defined as correlation of off-forward matrix.

Bjorken variable $x=\dfrac{Q^2}{2p\cdot q}$

Momentum transfer squared $t=\Delta^2$

Skewdness parameter $\xi=\dfrac{p^+-p'^+}{p^++p'^+}=-\dfrac{\Delta^+}{2P^+}$

$$\int\frac{dz^-}{4\pi}e^{ixP^+z^-}\langle p'|\bar\psi(-z/2)\gamma^+\psi(z/2)|p\rangle\Big|_{z^+=0,\vec z_\perp=0}=\frac{1}{2P^+}\left[H(x,\xi,t)\bar u(p')\gamma^+u(p)+E(x,\xi,t)\bar u(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u(p)\right]$$

$$\int\frac{dz^-}{4\pi}e^{ixP^+z^-}\langle p'|\bar\psi(-z/2)\gamma^+\gamma_5\psi(z/2)|p\rangle\Big|_{z^+=0,\vec z_\perp=0}=\frac{1}{2P^+}\left[\tilde H(x,\xi,t)\bar u(p')\gamma^+\gamma_5u(p)+\tilde E(x,\xi,t)\bar u(p')\frac{\gamma_5\Delta^+}{2M}u(p)\right]$$

Forward limit: PDFs

$$H(x,\xi,t)\big|_{\xi=t=0}=f(x),\quad \tilde H(x,\xi,t)\big|_{\xi=t=0}=\Delta f(x)$$

There is no analog in E and $\tilde E$.

First moments: Form factors

Dirac and Pauli form factors F_1, F_2

$$\int dx\,H(x,\xi,t)=F_1(t),\quad \int dx\,E(x,\xi,t)=F_2(t)$$

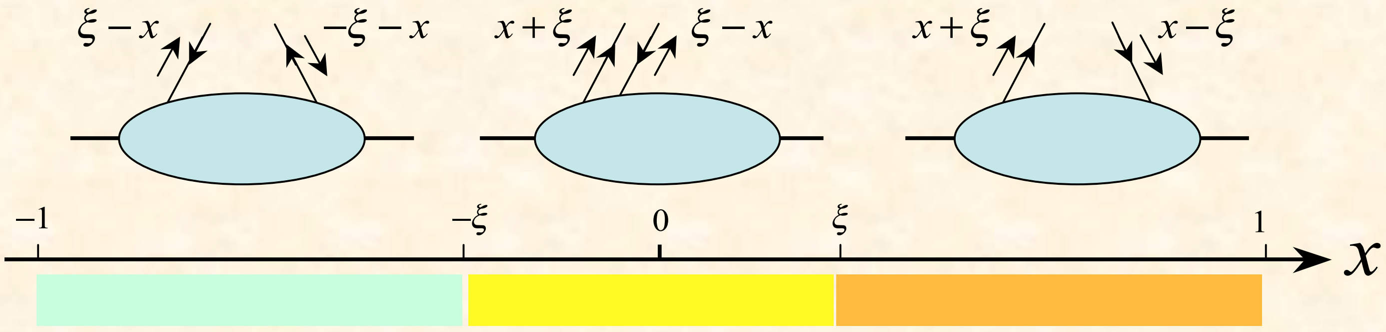
Axial and Pseudoscalar form factors G_A, G_P

$$\int dx\,\tilde H(x,\xi,t)=G_A(t),\quad \int dx\,\tilde E(x,\xi,t)=G_P(t)$$

Second moments: Angular momenta

Sum rule: $J_q=\dfrac{1}{2}\displaystyle\int dx\,x\left[H_q(x,\xi,t=0)+E_q(x,\xi,t=0)\right]$, $\quad J_q=\dfrac{1}{2}\Delta q+L_q$

GPDs in different x regions and GPDs at J-PARC



$-1 < x < \xi \quad (x+\xi < 0,\ x-\xi < 0)$

$-\xi < x < \xi \quad (x+\xi > 0,\ x-\xi < 0)$

$\xi < x < 1 \quad (x+\xi > 0,\ x-\xi > 0)$

Quark distribution

Emission of quark with momentum fraction $x+\xi$

Absorption of quark with momentum fraction $x-\xi$

Meson distribution amplitude

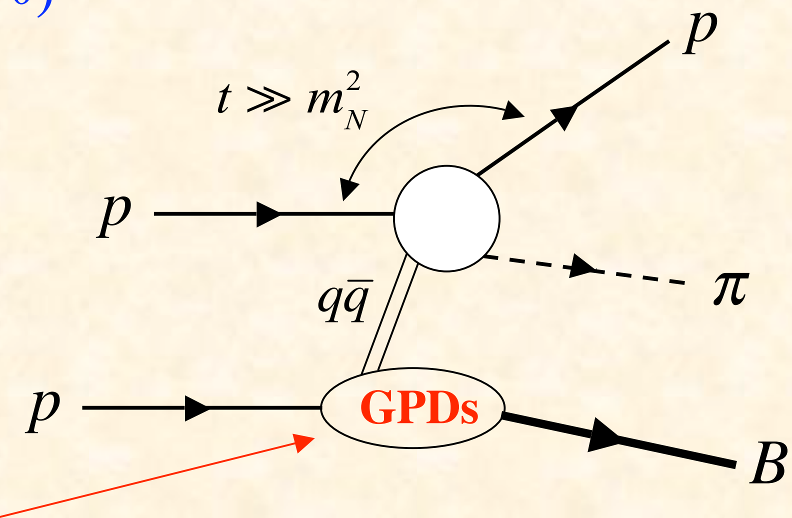
Emission of quark with momentum fraction $x+\xi$

Emission of antiquark with momentum fraction $\xi-x$

Antiquark distribution

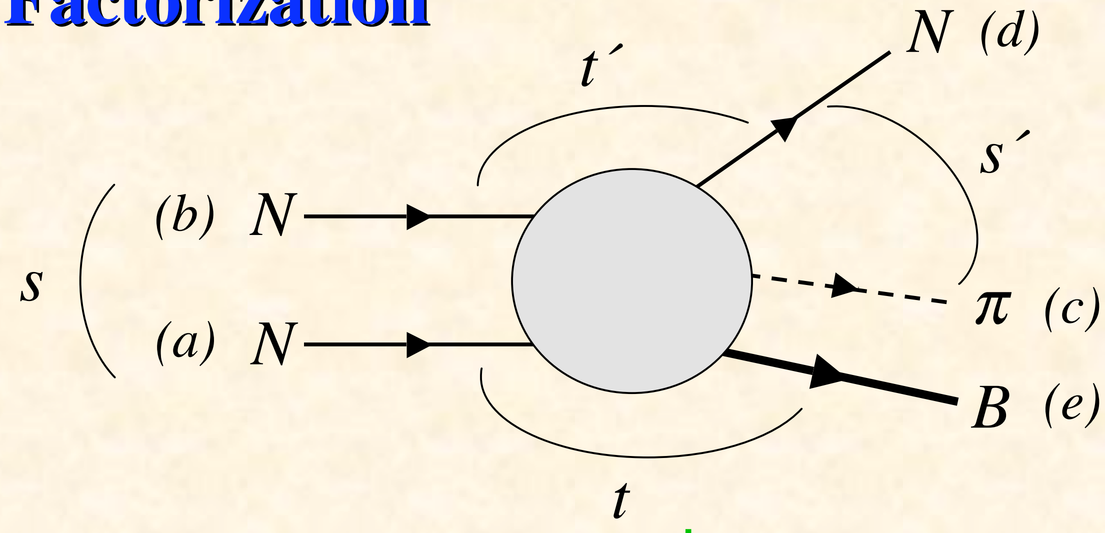
Emission of antiquark with momentum fraction $\xi-x$

Absorption of antiquark with momentum fraction $-x-\xi$



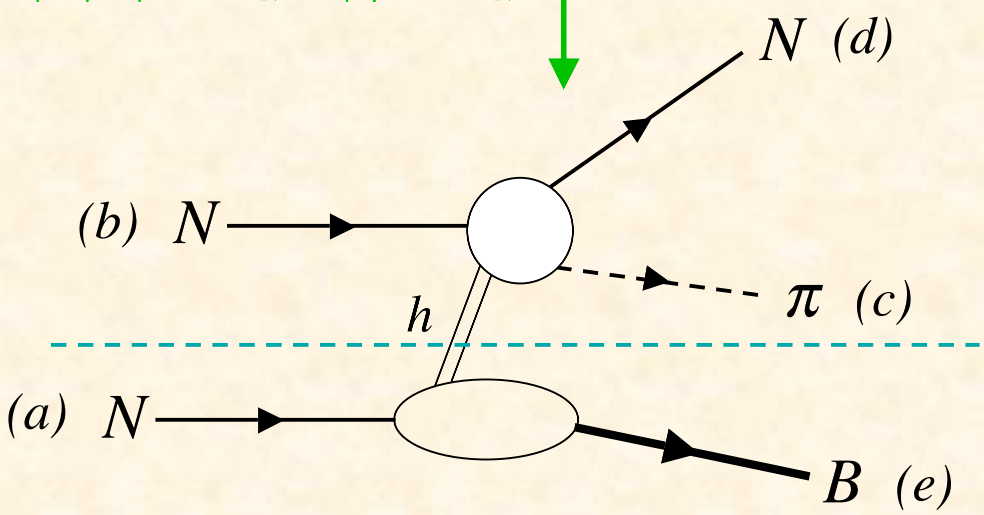
GPDs at J-PARC:
SK, M. Strikman, K. Sudoh,
arXiv:0905.1453

Factorization

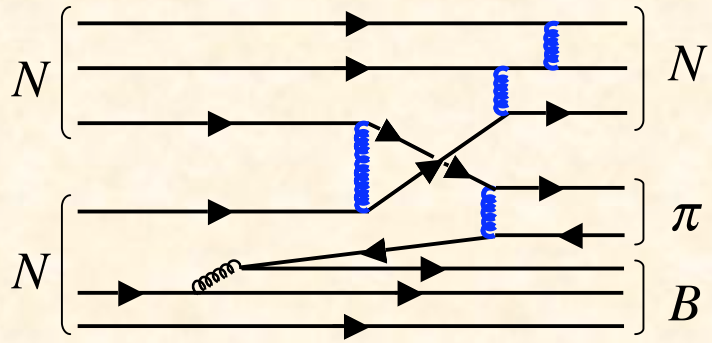


Consider a hard reaction with

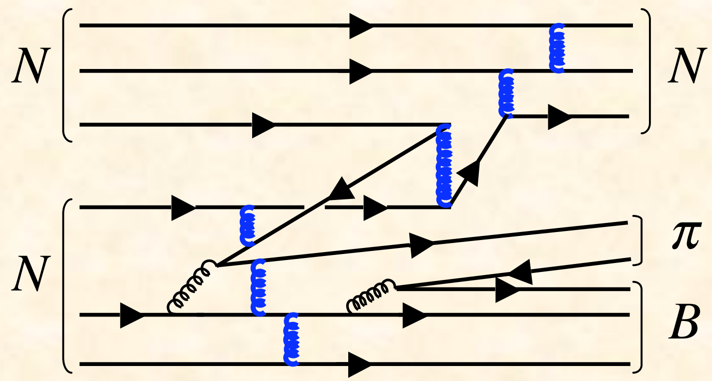
$$|s'|,\ |t'|,\ |u'| \gg M_N^2,\quad |t| \ll M_N^2$$

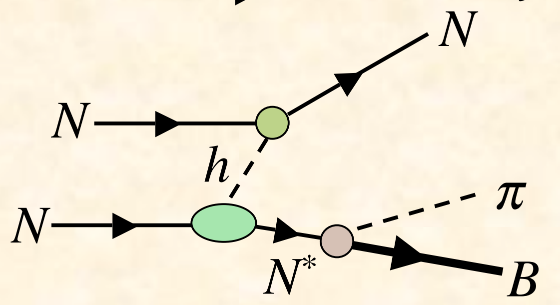


Typical leading process

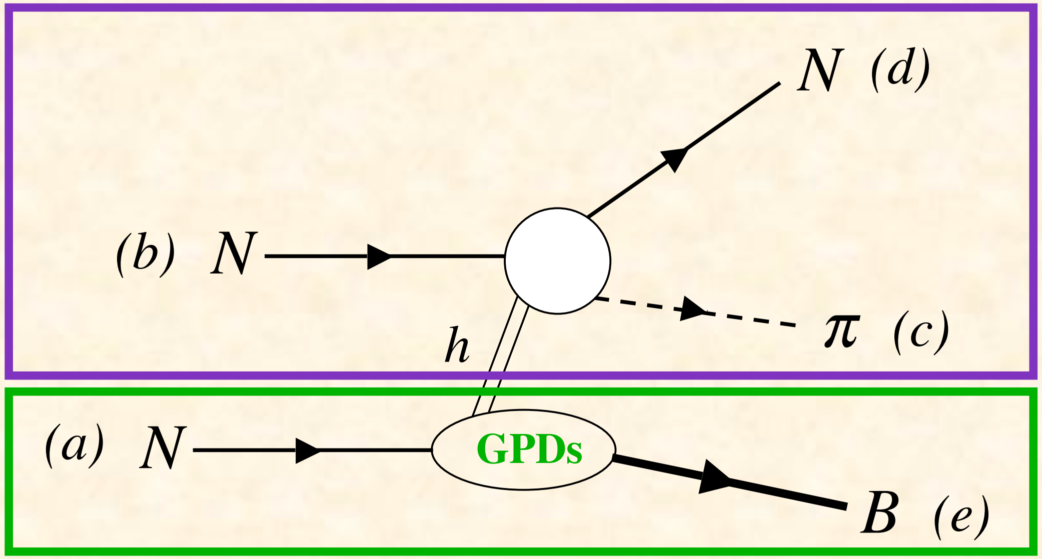


Typical sub-leading process
(cannot be factorized)
More hard gluon exchanges
→ suppressed



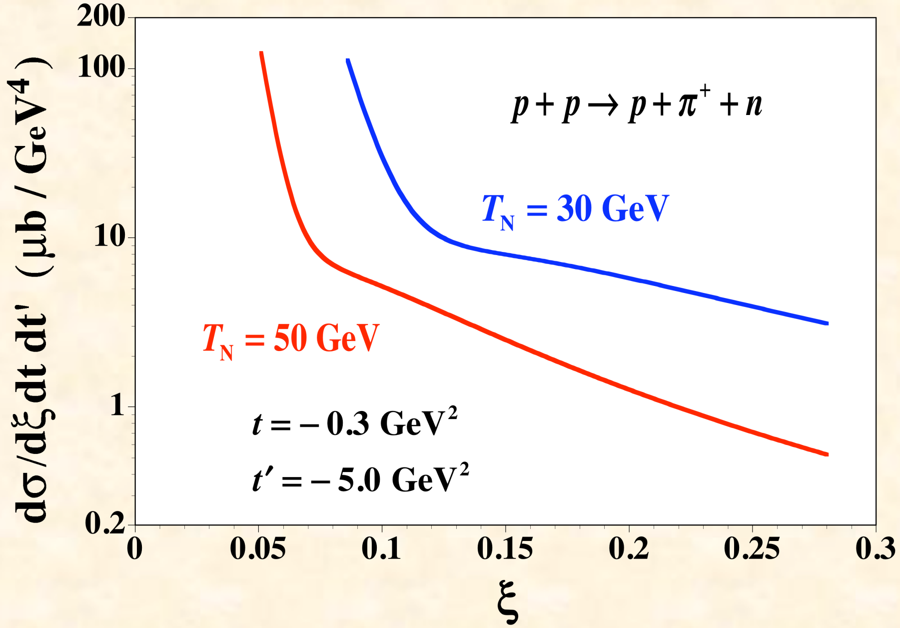


Cross section estimates



$\dfrac{d\sigma(s',t')}{dt'}$ so as to explain
AGS experimental data on
$\pi + p \rightarrow \pi + p, \ \ \pi + p \rightarrow \rho + p$

This part is expressed by GPDs.



At this stage, **our numerical results are for rough order of magnitude estimates on cross sections** by assuming π- and ρ-like intermediate states.

Still premature stage, need more works!

Exotic hadron search by fragmentation functions

Refs. (1) Scalar mesons in ϕ radiative decay,
F. E. Close, N. Isgur, S. Kumano,
Nucl. Phys. B389 (1993) 513.

(2) Proposal for exotic-hadron search
by fragmentation functions,
M. Hirai, S. Kumano, M. Oka, K. Sudoh,
Phys. Rev. D77 (2008) 017504.

Recent progress in exotic hadrons

$q\bar{q}$ Meson
q^3 Baryon

$q^2\bar{q}^2$ Tetraquark
$q^4\bar{q}$ Pentaquark
q^6 Dibaryon
…
$q^{10}\bar{q}$ e.g. Strange tribaryon
…
gg Glueball
…

(Japanese ?) Exotics

- $\Theta^+(1540)$?: LEPS
  Pentaquark?
  $uudd\bar{s}$?
- $S^0(3115)$, $S^+(3140)$: KEK-PS
  Strange tribaryons?
  $K^- pnn$
  $K^- ppn$?
- X (3872), Y(3940): Belle
  Tetraquark, $D\bar{D}$ molecule
  $c\bar{c}$
  $D^0(c\bar{u})\bar{D}^0(\bar{c}u)$
  $D^+(c\bar{d})D^-(\bar{c}d)$?
- $D_{sJ}(2317)$, $D_{sJ}(2460)$: BaBar, CLEO, Belle
  Tetraquark, DK molecule
  $c\bar{s}$
  $D^0(c\bar{u})K^+(u\bar{s})$
  $D^+(c\bar{d})K^0(d\bar{s})$?
- Z (4430): Belle
  Tetraquark, …
  Note: $Z(4430) \neq q\bar{q}$
  $c\bar{c}u\bar{d}$, D molecule?

Criteria for determining f_0 structure by its fragmentation functions

M. Hirai, SK, M. Oka, K. Sudoh,
PRD 77 (2008) 017504.

Possible configurations of $f_0(980)$

(1) ordinary u, d - meson $\quad \dfrac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$

Contradicts with experimental widths

$$\Gamma_{\text{theo}}(f_0 \to \pi\pi) = 500 - 1000 \text{ MeV} \gg \Gamma_{\text{exp}} = 40 - 100 \text{ MeV}$$

$$\Gamma_{\text{theo}}(f_0 \to \gamma\gamma) = 1.3 - 1.8 \text{ keV} \gg \Gamma_{\text{exp}} = 0.205 \text{ keV}$$

(2) strange meson, $\quad s\bar{s}$

(3) tetraquark $(K\bar{K})$, $\quad \dfrac{1}{\sqrt{2}}(u\bar{u}s\bar{s} + d\bar{d}s\bar{s})$

(4) glueball $\quad gg$

Contradicts with lattice-QCD estimate

$$m_{\text{lattice}}(f_0) = 1600 \text{ MeV} \gg m_{\text{exp}} = 980 \text{ MeV}$$

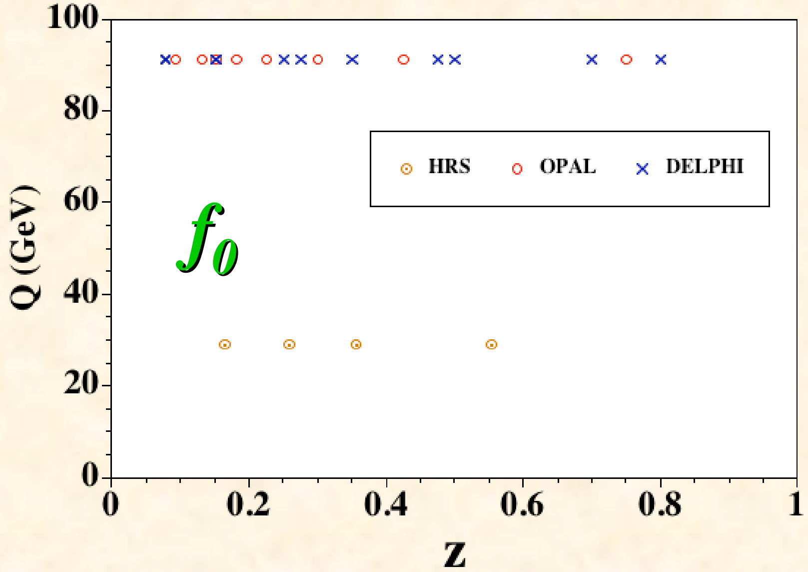
Discuss 2nd moments and functional forms (peak positions) of the fragmentation functions for f_0 by assuming the above configurations, (1), (2), (3), and (4).

Experimental data for f_0

Total number of data : only 23

Exp. collaboration	$\sqrt{s}$ (GeV)	# of data
HRS	29	4
OPAL	91.2	8
DELPHI	91.2	11

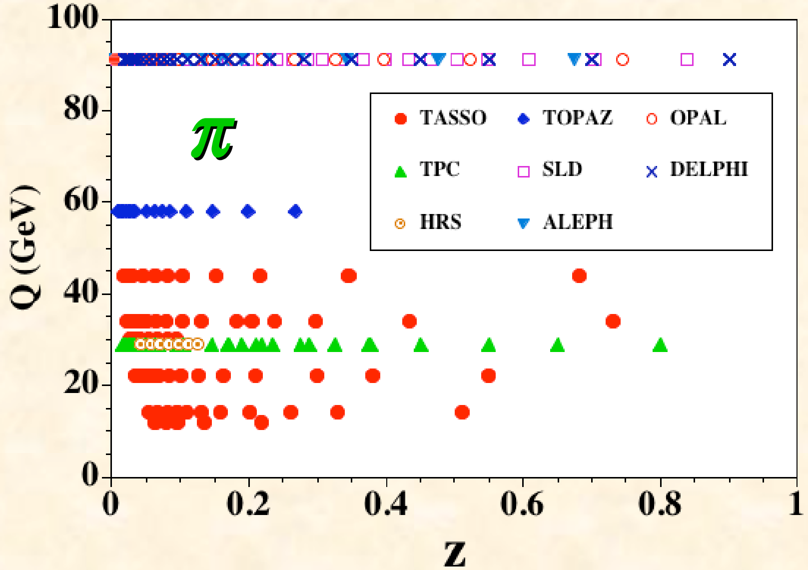
One could foresee the difficulty in getting reliable FFs for f_0 *at this stage.*



pion

Total number of data : 264

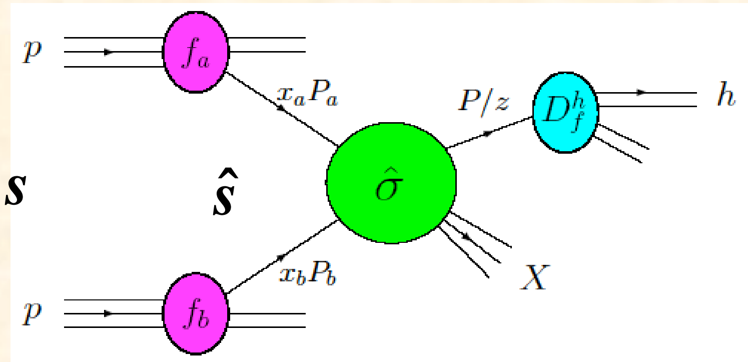
Exp. collaboration	$\sqrt{s}$ (GeV)	# of data
TASSO	12,14,22,30,34,44	29
TCP	29	18
HRS	29	2
TOPAZ	58	4
SLD	91.2	29
SLD [light quark]		29
SLD [c quark]		29
SLD [b quark]		29
ALEPH	91.2	22
OPAL	91.2	22
DELPHI	91.2	17
DELPHI [light quark]		17
DELPHI [b quark]		17



Fragmentation functions at J-PARC

Gluon and light-quark fragmentation functions have large uncertainties.

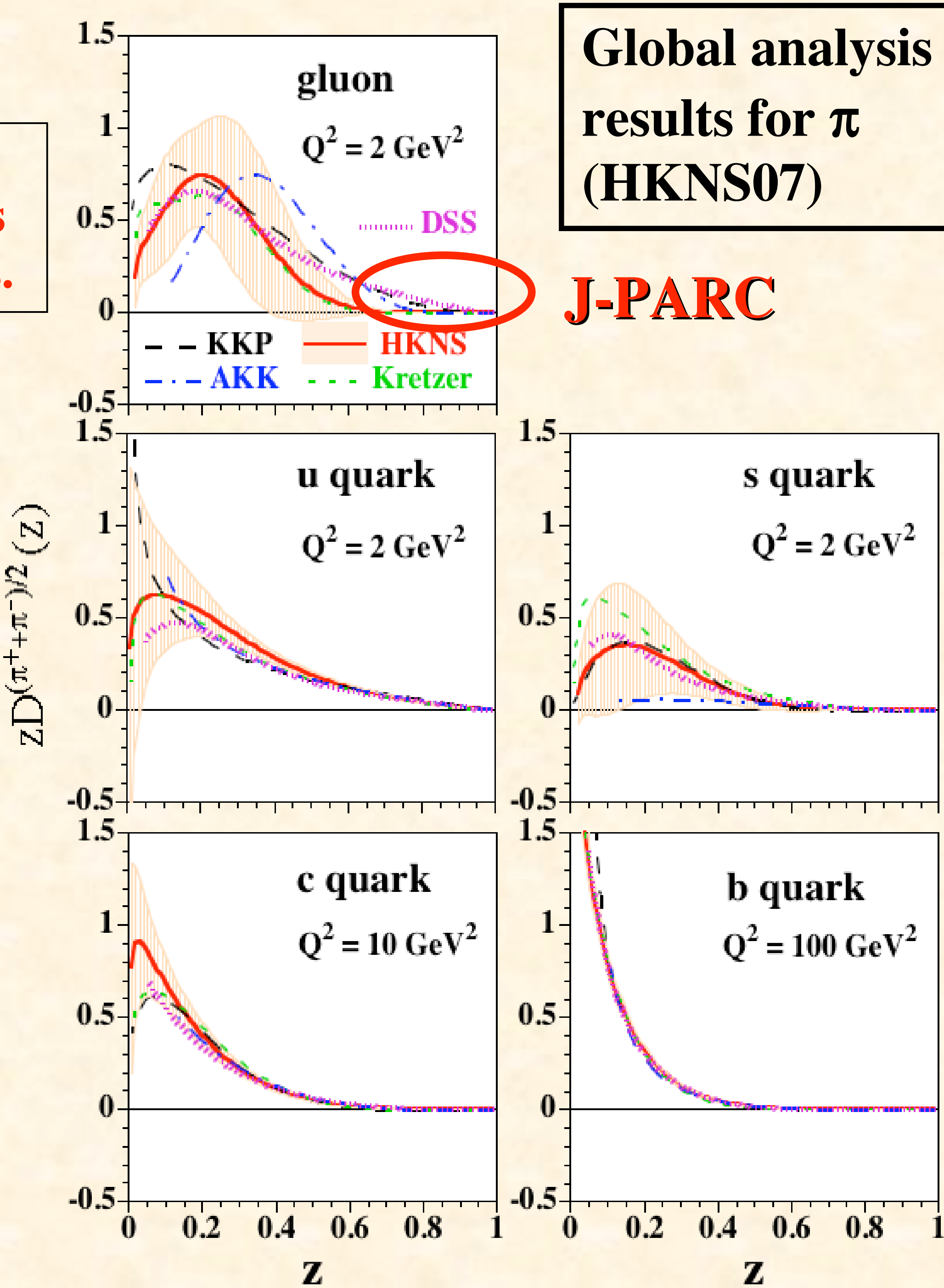
Large differences between the functions of various analysis groups.



$$\hat{s} = x_a x_b s \sim (0.4)^2 (10\ \text{GeV})^2$$

$$\sqrt{\hat{s}} = 0.4 \cdot 10 = 4\ \text{GeV}$$

$$z \sim \frac{p_T}{\sqrt{\hat{s}}\ /\ 2} = \frac{p_T}{2} \sim 1 \quad (\text{large } z)$$



Global analysis results for π (HKNS07)

Final comments

and

Summary

Issues for high-energy hadron project at J-PARC

- 30 GeV proton beam

→ Drell-Yan may not be an appropriate experiment
because data above the J/ψ mass are usually taken for PDF studies.
If data below the J/ψ can be used, it is a feasible experiment
in the beginning stage of J-PARC.

→ Charmed-meson production processes should be possible.
Two theoretical issues:
(1) pQCD corrections are larger than the ones of Drell-Yan,
and they may not be theoretically under control.
(2) Production mechanisms may not be well established.

→ Better ideas appropriate for the 30 GeV beam.
Elastic spin asymmetries, GPDs, …

- 50 GeV proton beam

→ Drell-Yan is possible. (First P906 at Fermilab in ~2011-2013, then at J-PARC.)
pQCD corrections are theoretically under control.

→ Many other *hard* processes … but the issue is 30→50 GeV cost.

Summary

There are interesting topics which could be investigated by using the primary 30-50 GeV proton beam.

- **Structure functions, spin physics, parton-energy loss, …**
- **Charm nuclear physics**
- **Large-*x* part of parton distribution functions**
- **Perturbative QCD**
- **Tensor structure at high energy**
- **Exotic hadron search by fragmentations**
- **Transition from quark to hadron degrees of freedom**
- **Short-range nuclear force**
- **Color transparency**
- **Generalized parton distributions**

Need
- **theoretical ideas and experimental feasibility studies**
- **attractive slogan(s) and public relations**

The End

The End